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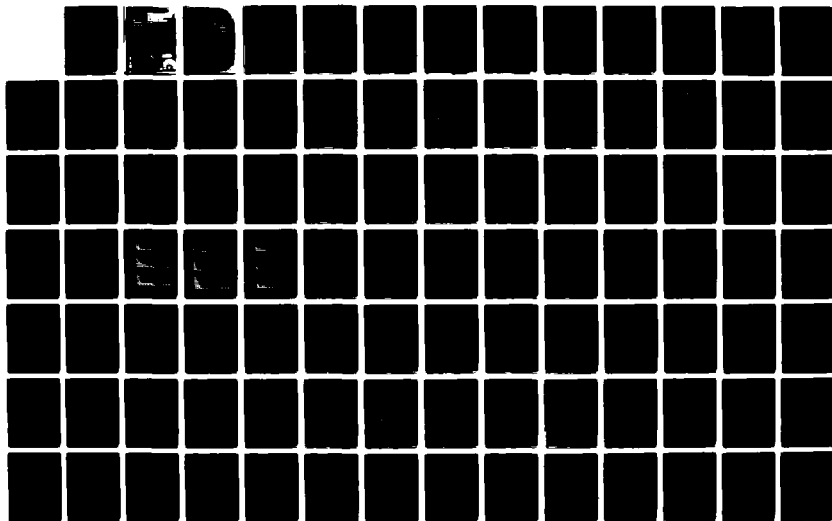
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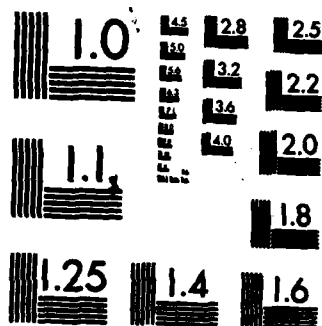
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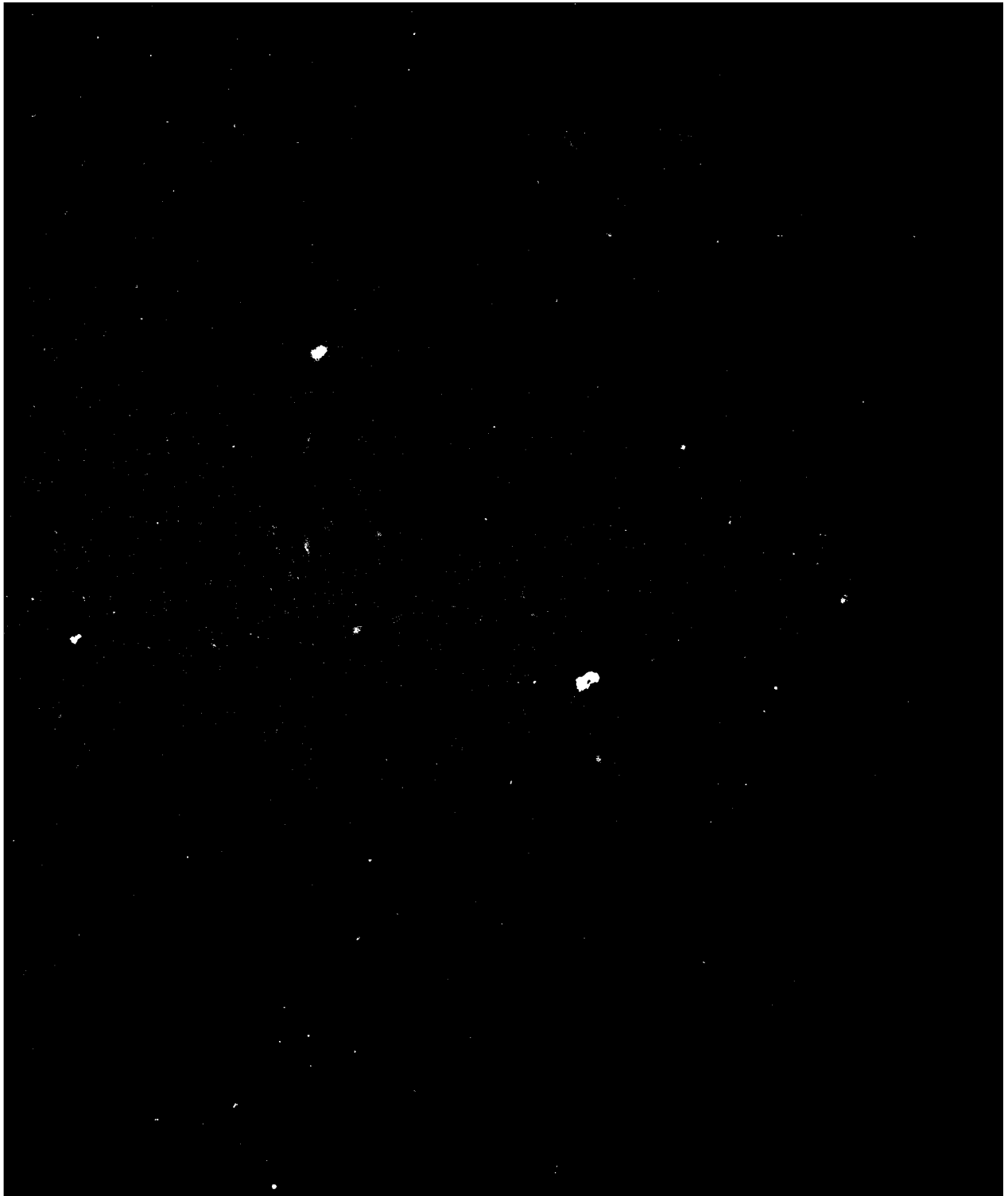
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16. Abstract <p>↓</p> <p>Radar information on the location, intensity, and movement of hazardous weather activity, is required by the Departments of Transportation, Defense, and Commerce. The three agencies have combined to develop a common, new radar system called NEXRAD, for NEXT generation RADAR. The current system lacks capability to detect wind related weather phenomena, and the new system is expected to use Doppler techniques, solid state technology, and improved processing. This report makes a preliminary assessment of costs and benefits of the NEXRAD program, concluding that the program is cost beneficial, but that not enough is known about the new system's capability to discriminate among alternative numbers and sophistication of radars in the system.</p> <p>Data on losses are reported for nine separate weather hazards: floods, tornadoes, thunderstorms, hurricanes, windstorms, severe winter storms, turbulence, icing, and hail. Estimates are made of those losses avoidable with the new system.</p>			
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FOREWORD

This assessment is Preliminary. It is the first comprehensive assessment of the costs and benefits of a proposed Next Generation Weather Radar (NEXRAD) System for the United States.

Results have been derived using available data bases and sources in full recognition that weather radars with the performance characteristics postulated for NEXRAD deployment have not been used operationally as a system to detect, measure, and track hazardous weather phenomena.

This report, accomplished under contract with the Federal Aviation Administration, represents a contribution to the NEXRAD System acquisition process by the Federal Aviation Administration.

EXECUTIVE SUMMARY

Purpose of the NEXRAD Program

Performing missions for the Departments of Commerce, Defense, and Transportation requires information on the location, intensity, and movement of hazardous weather activity. This information is currently obtained from a combination of weather and air traffic control radars. However, the weather radars lack capability to detect wind-related weather phenomena, and are difficult to maintain due to their age. The air traffic radars cannot detect wind either, and are also limited because they are optimized for detecting airplanes, not precipitation.

As a result, the three departments have proposed a common, new system called NEXRAD, for NEXT generation RADar. This national system is intended to provide hazardous weather information within limitations of cost and technical feasibility. A major upgrading of existing capability is anticipated, primarily through application of the Doppler principle, the use of solid state technology, and improved communication, display, and data processing devices.

Purpose of This Study

This report is a preliminary assessment of costs and benefits of the NEXRAD program. The program is in the early stages of development, approaching the first of four mandated "key decisions" in the major systems acquisition process. After this first decision, the Government would normally solicit design concepts. This study documents the wisdom, from a costs and benefits point of view, of proceeding into the design concept stage. As more is known concerning the program--the concept(s) selected for development, the likely costs of the equipment, and operational plans for utilizing the new information--the analysis presented here can be greatly refined.

Conclusions

Benefits exceed costs for the NEXRAD program. The benefits to the nation from hazardous weather warnings due to deployment of the NEXRAD system are estimated in a range of \$210 to \$590 million annually, varying according to radar type and system mix. Benefit to cost ratios range between 6 and 13 to 1. Net present values range from \$800 to \$2,000 million.

Any deployment scenario that includes Doppler radar has a higher net present value than a non-Doppler scenario. The advantages of deploying all Doppler radars, versus a mix of Doppler and non-Doppler radars, are too close to call. Six hypothesized

deployment scenarios were analyzed to evaluate the range of benefits likely. One scenario had no Doppler radar, two had a mix, and three had all Doppler radars of differing sophistication. A network of 140 weather radars was assumed, with mixed deployments consisting of 95 Doppler and 45 non-Doppler installations. Location of the Doppler weather radars are in the thunderstorm, tornado, and hurricane prone areas.

The net present value of any system that included Doppler was at least twice that of an all non-Doppler system, although even the non-Doppler system had a benefit to cost ratio of six. A sensitivity analysis shows that a decision to begin Doppler radar deployment is sound. The same analysis, however, showed that selection among deployment strategies is very sensitive to the assumptions, and should be reexamined as the capabilities of the systems to be developed are better known.

No allocation of benefit to each of the three sponsoring departments is possible from the data available at this time. This analysis focuses principally on the catastrophic property losses from severe weather, because they are the largest and best documented. Operational losses, such as airlines avoiding storm delays, the military avoiding unnecessary protection of aircraft when a poorly forecast storm did not materialize, or a civilian construction worker able to pour concrete because a specific forecast possible with NEXRAD showed the storms would affect him, are not well documented.

The major beneficiary of NEXRAD will be the general public, a not surprising conclusion because the general public as a group is far larger than the military or aviation communities. Interviews conducted during the study and comments for the draft report suggested that the Department of Defense (DOD) and the constituencies of the Department of Transportation (DOT) would derive major operational benefits from NEXRAD. Relatively little data are available presently that specifically relate to these operational benefits. A more refined allocation among the sponsors should include further examination of these types of benefits.

Analysis of Benefits

Methodology

The analysis gathered value of catastrophic losses in nine categories of severe and hazardous weather: Flood, tornado, thunderstorm, hurricane, wind, severe winter storm, turbulence, icing, and hail. When possible, the analysis gathered property damage, death and operational losses, and segregated them into three constituent groups--general public, military, and civil aviation.

Then, the values were examined and a percentage of the losses which could be avoided with NEXRAD warnings was determined. Finally, an estimate of the relative capability (or performance) of each of the deployment scenarios was applied to the percentages,

resulting in an avoidable loss benefit for each scenario.

The performance characteristics of the proposed new weather radars composing the deployment scenarios have not been proven through operational use. To relate deployment scenarios to benefits, 21 noted weather radar experts were asked to estimate a percentage "performance improvement" of new equipment over the equipment in the existing network.

Data Limitations and Assumptions

An adequate warning capability was assumed. Recent hazardous weather loss data were assumed to reflect the performance capabilities of today's weather radar systems. The system in this sense includes the function of disseminating the information to someone who can take action to avert a loss, as well as generating the warning from the basic information. It is assumed that when a more effective radar system is in place, that users can be effectively warned, and that they are prepared to take action as a result of the warning.

Routine forecasts of non-severe weather may also be improved by NEXRAD, but were not quantified. The capability of Doppler radar to measure continuous winds aloft data is not well understood. Neither the wind measuring capability of the selected Doppler radar, nor how this capability of the selected Doppler radar could be applied to non-hazardous weather forecast services is known, and is therefore not quantified.

Although the NEXRAD system encompasses weather radars to be installed both in the United States and overseas, this study deals with only those radars to be deployed in the conterminous United States.

Analysis of Costs

Assumptions

The NEXRAD system is defined to include hardware, software, facilities, communications, logistics, training, personnel, and procedures. Costs include development, production, and program management as one-time costs as well as operations and support as recurring costs. Computations of the investment criteria are based on 25 years of system life.

Additional costs to adapt the system to specific users, and to disseminate the information to the general public, have not been included. The system designers will specify several weather radar "products", such as maps, textual summaries, and digital data obtainable by telephone. Costs for FAA or the military to further interpret or transmit that data to controllers or pilots are not estimated.

INTRODUCTION

Purpose

The purpose of this report is to provide the results of an initial quantification of the costs and benefits of the proposed Next Generation Weather Radar (NEXRAD).

NEXRAD is proposed to provide improved weather radar information, thus improving day-to-day routine radar observations and increasing the accuracy, timeliness, and credibility of warnings of severe thunderstorms, tornadoes, flash floods, turbulence, wind shear, and other types of hazardous weather-related events.

The NEXRAD System contemplates the operational deployment of a new generation of weather radars for national use. The proposed network of weather radars has the potential for satisfying many of the common mission needs for the detection and prediction of hazardous weather of the Department of Commerce (DOC), Department of Defense (DOD), and the Department of Transportation (DOT). A Joint System Program Office (JSPO) has been established within DOC with representation and support from DOD and DOT that will have overall responsibility for system acquisition of NEXRAD under the procedures of OMB Circular A-109.

Scope of Study

This study is a preliminary assessment of the costs/benefits allocable to the proposed Next Generation Weather Radar (NEXRAD) System. It draws upon many sources of published information, discussions with agency personnel, and a survey of weather radar experts.

General Assumptions

The NEXRAD System encompasses weather radar systems to be installed both in the United States and overseas; however, this study is concerned only with those radars that will be installed in the conterminous United States. NEXRAD includes the radars provided for common use (NEXRAD network radars). The radar systems provided primarily to meet a single user's needs are not considered in this assessment. The NEXRAD System is defined to include hardware, software, facilities, communications, logistics, training, and staff, together with operational training and maintenance procedures.

The number and location of the radars in the NEXRAD System is under evaluation by the NEXRAD JSPO. In addition, the JSPO will evaluate the relative value of the deployment of a mix of Doppler and non-Doppler weather radars. The initial assessment that is being accomplished under this study addresses the issue of the Doppler/non-Doppler mix. The need to deploy a NEXRAD system has

almost reached crisis proportions because many of the radars in the current network have been in use more than 20 years and the availability of the radars has been steadily decreasing (presently between 80 to 85 percent).

This report, accomplished under contract to the Federal Aviation Administration (FAA), is to aid in providing the NEXRAD JSPO and other Federal agencies information on which to base subsequent decisions concerning NEXRAD. The overall cost/benefit assessment represents a contribution to the NEXRAD System acquisition process by the Federal Aviation Administration.

Recent annual cost and loss data due to hazardous weather are assumed to reflect the performance capabilities of today's weather radar system. This assumption includes losses due to dissemination difficulties as well as losses due to warning system deficiencies and lack of response by the user. In order for benefits to be fully realized, it is assumed that an effective warning dissemination system will be in operation at the same time that a more effective weather radar system is introduced. Further, it is also assumed that effective preparedness plans and procedures have been established. The Federal plan for meteorological services and supporting research for fiscal year 1974 made the case quite succinctly that it is the combination of timely and accurate warnings in addition to effective preparedness activities that reduces the deaths from natural disasters.

Overall Constraints

The information available for determining the costs of hazardous weather in terms of loss of life, injury, property loss, disaster relief, federal government loan assistance, and costs to individuals and communities due to transportation and other losses is inadequate. This fact imposed limits on the detail in which the analysis of costs and the derived benefits were carried out and probably results in a significant underestimate of the total costs of hazardous weather.

Mission Needs Summary

General

The mission of NEXRAD is the acquisition, processing, and distribution of weather radar information to aid in reducing loss of life, injuries, and damage to property. This radar system addresses the common need among three Federal agencies (Departments of Commerce, Defense, and Transportation) for information on the present location, severity, and movement of weather phenomena, both routine and hazardous, throughout the United States, including tornadoes, severe thunderstorms, heavy precipitation, tropical cyclones, hail, high winds, and severe turbulence.

Principal User Mission

DOC, DOD, and DOT have major weather-related missions and responsibilities that require weather radar information.

DOC, through its National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS), is the principal civilian meteorological agency of the Federal Government. Specifically, DOC is responsible for detection of hazardous weather such as severe thunderstorms, tornadoes, floods, and winter weather events in addition to warning the public. It is also responsible for providing essential weather information for other activities such as civilian aviation, agricultural and forestry operations, marine activities, and the entire river and flood prediction program. DOC operates many weather radars and uses information from some radars operated by DOD and DOT to meet these responsibilities.

Within DOD, the Air Force's Air Weather Service (AWS) provides worldwide meteorological and aerospace environmental services to the Air Force, Army, and certain DOD elements; the Naval Oceanography Command (NOC) supports the Navy, Marine Corps, and some elements of DOD. These organizations are responsible for providing and/or relaying severe weather warnings for the protection of DOD resources and personnel, providing weather information to aid in the decision-making process at specific locations, and supporting military aviation. To meet these responsibilities, DOD operates weather radars in the United States and overseas and uses information from these and from DOC and DOT radars in the conterminous United States.

DOT, through FAA, is responsible for the safe and efficient utilization of the U.S. airspace. In meeting these responsibilities, the FAA provides information on the location and intensity of potentially hazardous weather conditions to pilots and others concerned with aviation. In recent years, there has been an increased emphasis on providing real-time hazardous weather information. DOT has no weather radars and presently obtains its information from its own air traffic control radars (not designed for weather detection) and from NWS radars via remote displays, other NWS products, and NWS personnel located at FAA facilities.

Other Users

For NEXRAD to truly serve the nation, the system design must address the needs of other potential government and non-government users.

Requirements of Federal agencies other than NWS, DOD, and FAA are considered through the Federal Committee for Meteorological Services and Supporting Research. Unless otherwise stated, it is assumed that satisfying the requirements of the three principal agencies will satisfy other agency requirements.

Non-government users include universities, researchers, and teachers, private meteorological firms, and the news media, among others.

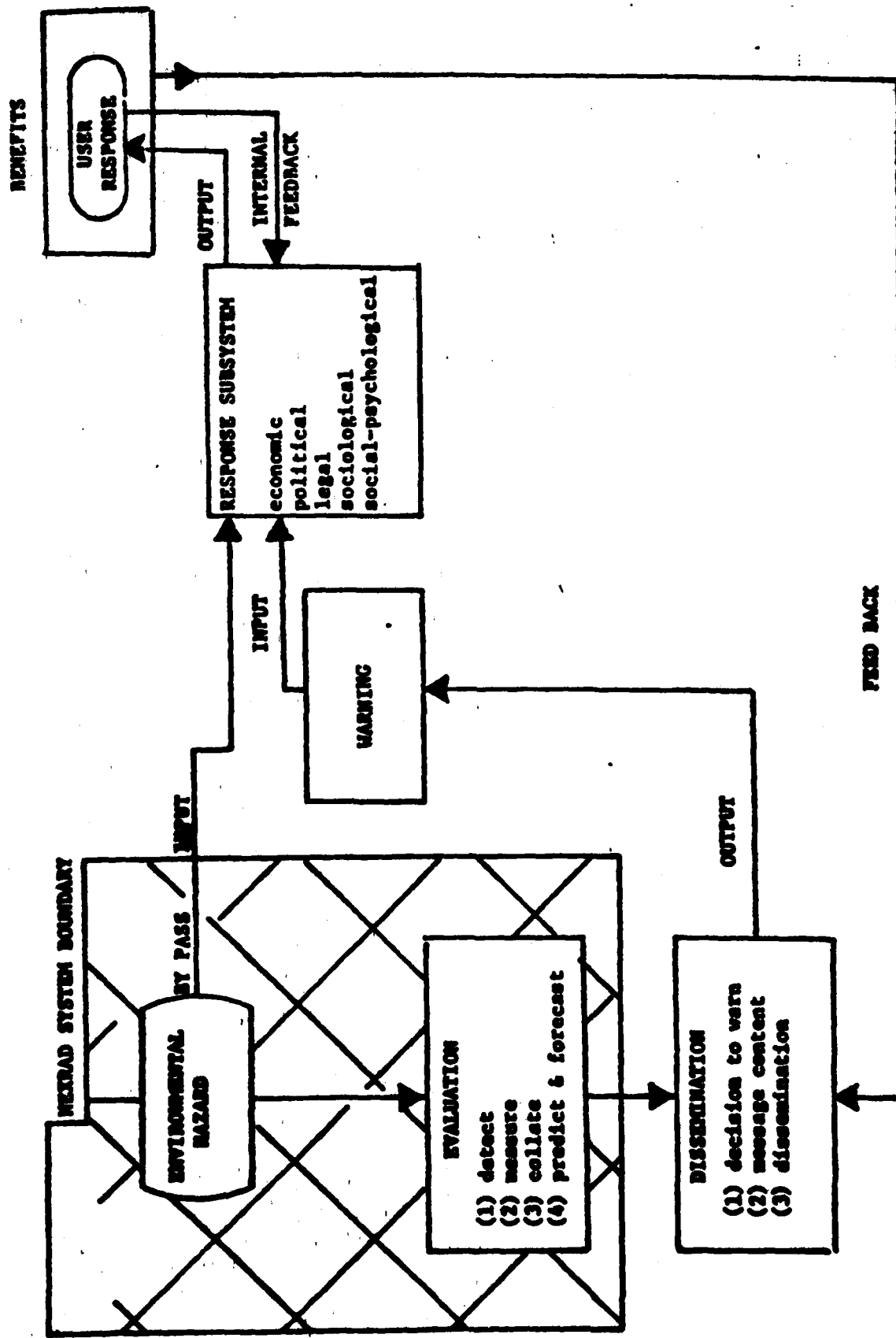
Approach

Hazardous weather detection, location, measurement, and tracking is the primary function of a weather radar network. Each type of hazardous weather--tornadoes, flash floods, thunderstorms, wind, severe winter storms, turbulence, hurricanes, and icing--possesses different physical characteristics that have direct implications for warning systems and require relatively quick response in order to avert catastrophe and assure human safety.

This report provides preliminary cost estimates for the proposed NEXRAD System and postulates benefits that will accrue from the operation of such a system. The proposed NEXRAD system provides an excellent means of reducing loss of life, injury, or property damage due to hazardous weather. The quick response needed to avert loss is dependent on more than an improved national weather radar network. An integrated warning system includes not only the evaluation of the hazard that is provided by the weather radar, but also the dissemination subsystems. Figure 1, Systems Model of a Warning System (Mileti 1975), bounds the NEXRAD System and shows NEXRAD in the context of an integrated warning system.

The NEXRAD costs in 1980 dollars are estimated as life cycle costs. The products from a NEXRAD radar are shown in Table 1. The benefits are those that are postulated to accrue to the user as the decision maker and the individual(s) who respond to the warning.

The costs of hazardous weather to the nation are categorized, where the data are so stratified, as: property damage, injury, death, operational losses, and a "catch-all" category of items difficult to assess, such as loss insurance, value of life, etc. Figure 2 illustrates the matrix of information required for an ideal data set of the parameters involved in this study. Unfortunately, available data lump many of the users, phenomena, and costs together. Such aggregation imposed limits on the detail in which an analysis of costs was carried out.



FROM: Mileti, D.S. (1973)

Figure 1.--Systems model of a warning system and a NEXRAD system bounds.

Table 1.--Products from use of weather radar data

Unique Doppler Capability Indicated by * Symbol
Data Are Accomplished by Positional and "Housekeeping" Information

Base Data

- Reflectivity
- * Radial Wind Velocity
- * Radial Velocity Spectrum Width

Derived Data

- Intensity
 - a. Precipitation Rate
 - * b. Velocity--Horizontal and Vertical
 - * c. Turbulence
- * Change of Intensity
- Change of Reflectivity
- Movement--Area, Line, and Cell
- Cumulative Precipitation
- Centroid Location
- * Cell Rotation (Vorticity)
- Areal Extent
- Rate of Areal Growth
- Vertical Extent
- Rate of Vertical Growth
- * Internal Convergence/Divergence
- * Vertical Shear
- * Horizontal Shear
- * Vertical Wind Velocity
- * Horizontal Wind Velocity
- Duration
- * Extrapolation--Position and Parameter
- Magnitude

Source: Approved NEXRAD JOR

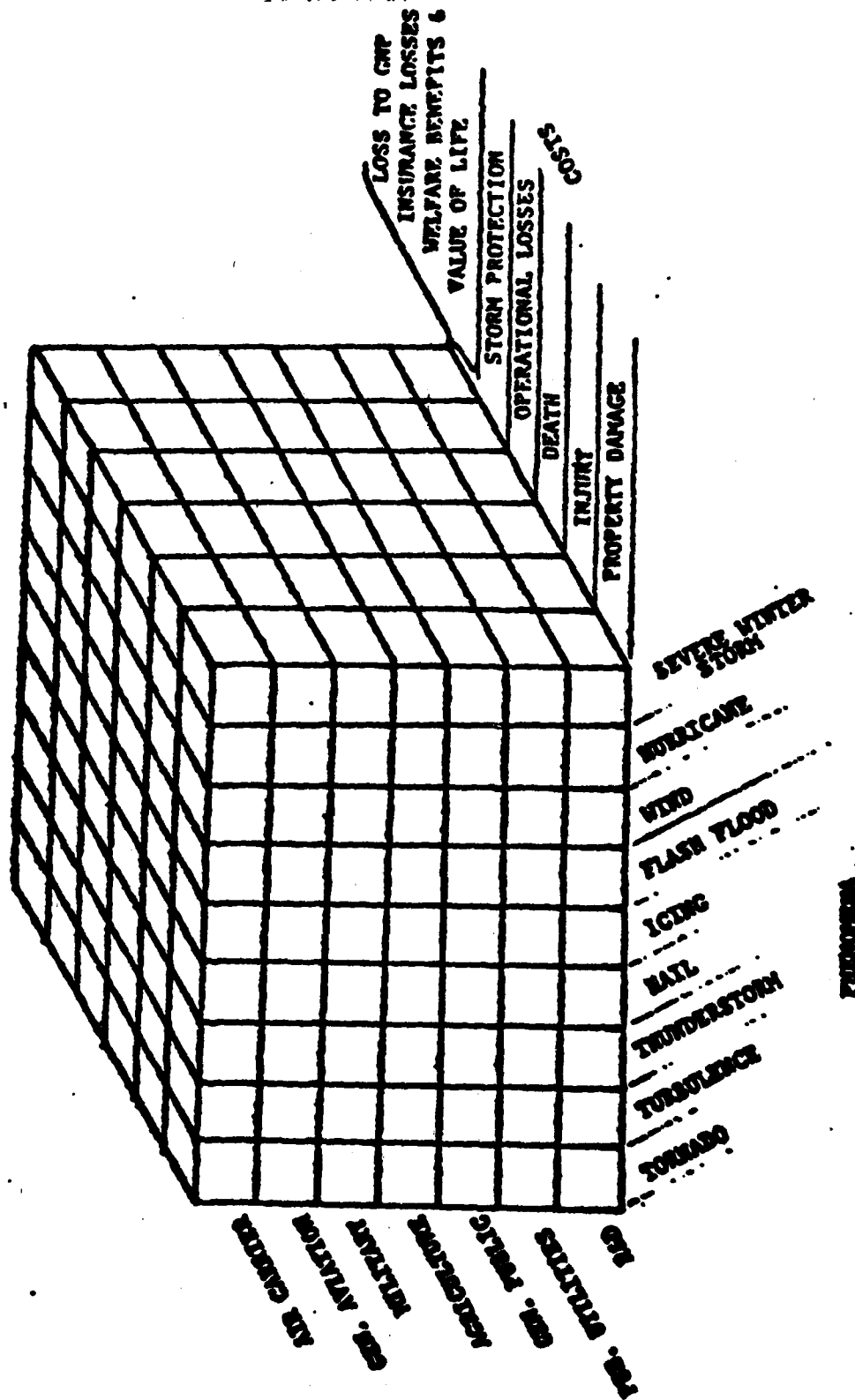


Figure 2.--Storm related costs and other factors
(matrix for cost/benefits)

THE PRESENT SYSTEM--BASELINE ANALYSIS

The present weather radar system is described in terms of radars used in the basic national weather radar network and radars used primarily for local warning purposes.

The National Weather Radar Network

This network of radars (OFCM 1979), operates around the clock to detect, describe, and monitor the development and movement of significant convective weather and also provides information to the DOC and DOD field offices for local warnings. The DOC provides a dedicated operation and maintenance staff of 4 to 6 persons for each of the network radars.

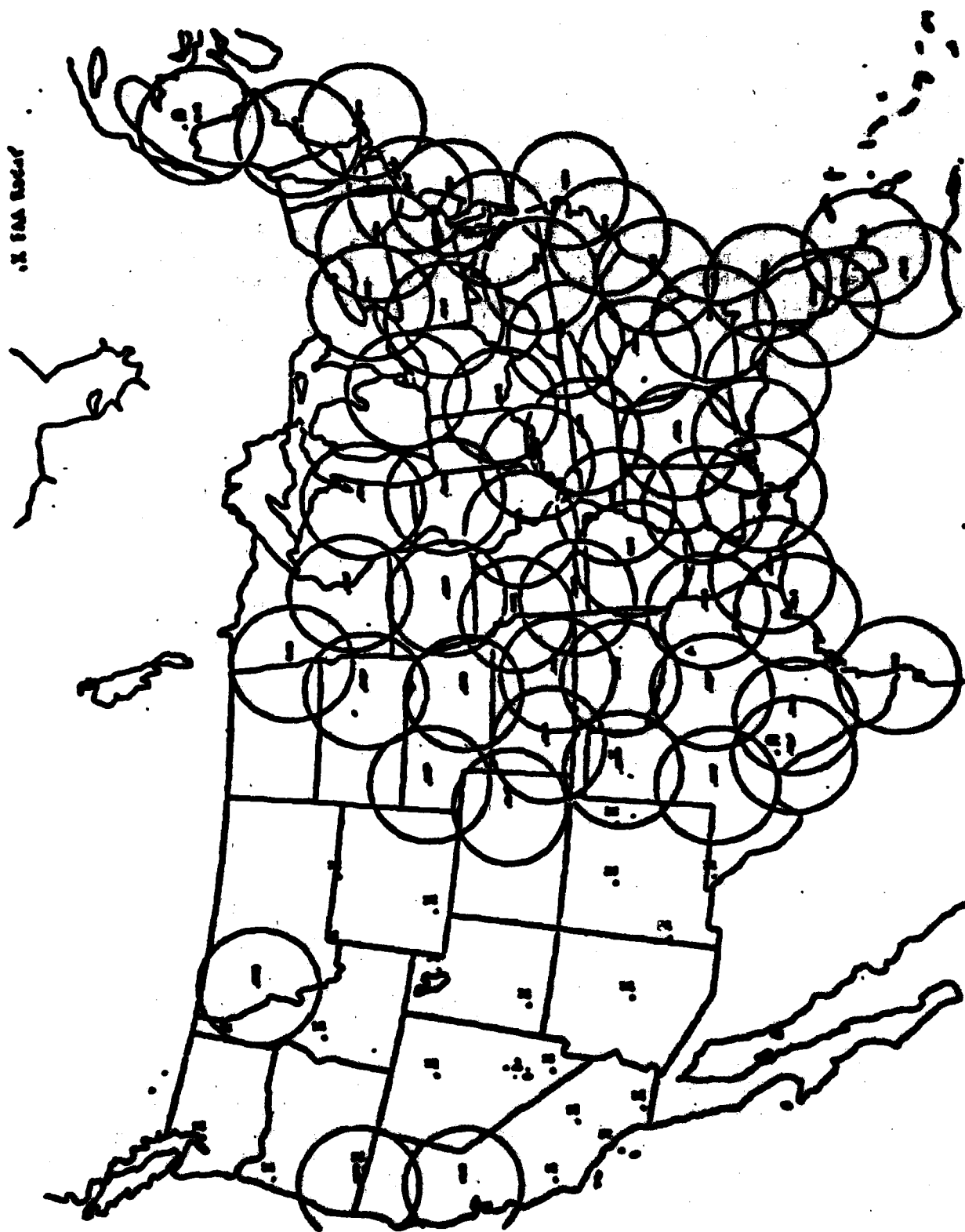
The network consists of 51 WSR-57 and 5 WSR-74S NWS radars, 2 FPS-77 AWS radars, and 22 DOT air traffic control radars. DOC personnel use remote displays from the radars at four Air Route Traffic Control Centers (ARTCCs) and prepare information for both network and local warning purposes in the western intermountain area. Figure 3 shows the location of these network radars.

Hourly and special radar observations are provided by network radars in alphanumeric format, and, if required, as narrative interpretations of the data. The "hourlies" are automatically composited at the National Meteorological Center and distributed nationally via facsimile and teletype. Thirty-seven of the network radars have remoting system transmitters that permit sending relatively low resolution reflectivity images and annotated remarks to other offices over a facsimile system using conventional telephone lines. DOD, DOT, and non-government users make use of this remoting capability by both dedicated and "dial-up" circuits.

Local Warning Radars

Local warning radars are operated by DOC and DOD to supplement the basic network in areas of high severe storm risk where network coverage is inadequate. The basic U.S. weather radar network is supplemented by 65 DOC and 84 DOD local warning radars as shown in Figure 4. DOD also has 26 of its local warning radars located at bases outside the United States. DOD radar requirements at 22 other U.S. locations are provided with remoting devices and no radars are available for an additional 6 overseas requirements.

Designated local warning radars function as backups to the basic network and attempt to pick up the network responsibilities when a primary radar fails. The effectiveness of the arrangement is limited due to the characteristics of the radars and the fact that no dedicated operators are provided for local warning radars.



36-MS, 2-MS, 22-FAA RADAR SITES

Figure 3.--Basic national weather radar network

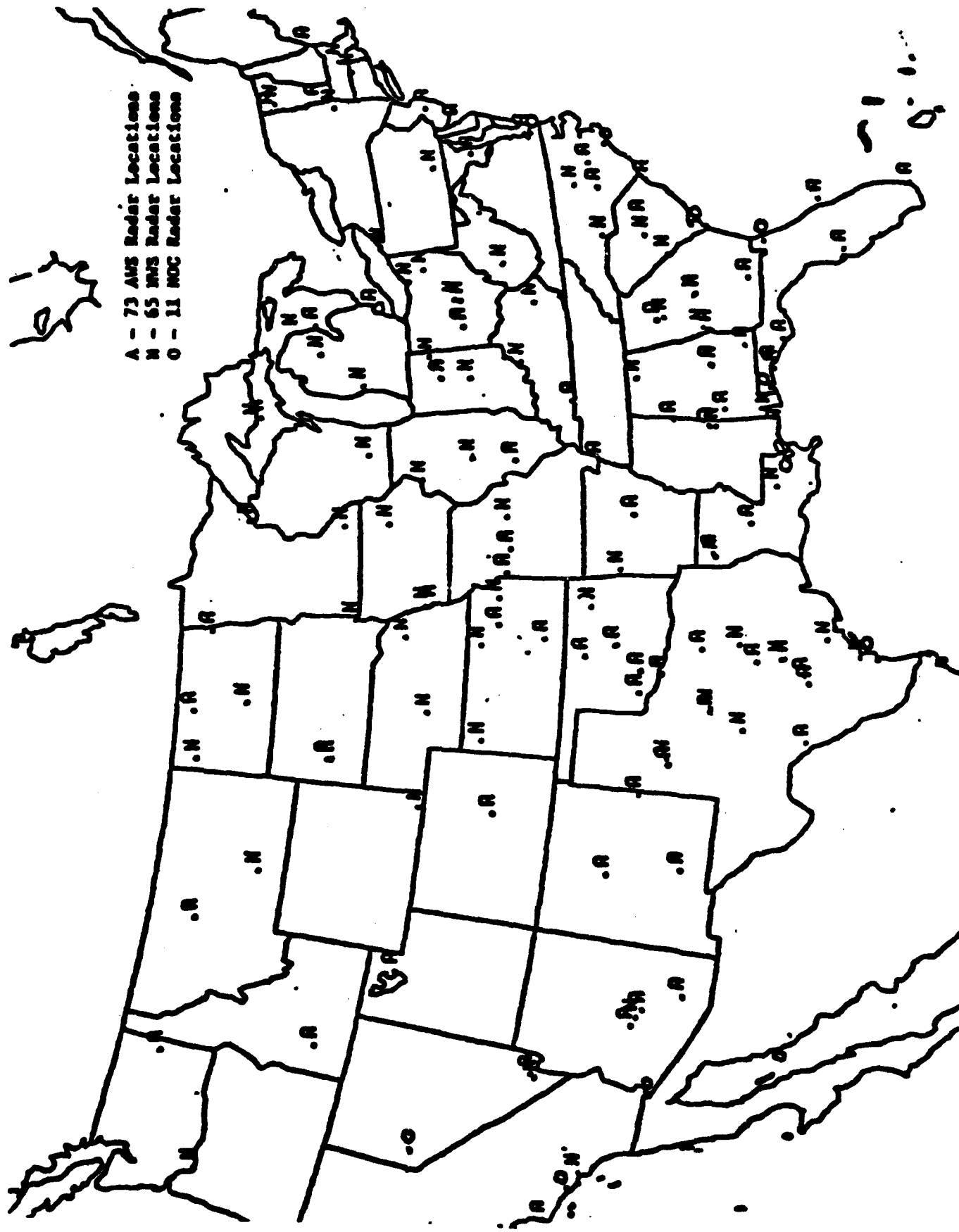


Figure 4.--Local warning radars

Limited weather information is also currently available for air traffic control purposes from all air traffic control radars. This information is obtained when severe weather echoes "break" through the weather suppression circuitry or when the controller momentarily overrides the suppression circuits to view the weather echoes. This procedure has been implemented so as not to jeopardize air traffic control functions.

Airborne Weather Radar

Although a national inventory of airborne weather radars is not available, a major supplier of these radars (the Bendix Corporation) has delivered approximately 26,000 weather radar systems for use on air transport, general aviation, and military aircraft since 1970 (private correspondence from W. J. Blizzard, the Bendix Corporation). Airborne weather radars are required as standard equipment on most aircraft carrying passengers for hire and are also installed on many other aircraft to provide the pilot with real-time information on the location and intensity of storm clouds. For example, the U.S. Air Force had 5,260 airborne weather radars on aircraft as of November of 1980. This number included Air National Guard and Air Force Reserve aircraft (Capt. Knutson, HQ AWS, Telecon, November 1980).

Airborne radar is a valuable tool; however, its use is primarily as an indicator of storm locations for avoidance purposes while enroute. The FAA provides the following advice to the pilot concerning use of airborne weather radar: "Airborne weather avoidance radar is, as its name implies, for avoiding severe weather--not for penetrating it. Whether to fly into an area of radar echoes depends on echo intensity, spacing between the echoes, and the capabilities of you and your aircraft. Remember that weather radar detects only precipitation drops; it does not detect turbulence. Therefore, the radar scope provides no assurance of avoiding turbulence. The radar scope also does not provide assurance of avoiding instrument weather from clouds and fog. Your scope may be clear between intense echoes; this clear area does not necessarily mean you can fly between the storms and maintain visual sighting of them." (FAA Advisory Circular No. 00-24A, 1978.)

Typically, an X-band or C-band airborne weather radar will be capable of detecting a storm of moderate intensity at 150 to 300 nautical miles from altitudes of 15,000 to 35,000 feet, respectively, identify storm system patterns at 100 to 150 nautical miles, and resolve areal extent and intensity of individual cells from 20 to 75 nautical miles (Meritt 1967).

Enroute, a nominal 5- to 10-minute time period is used to: detect the hazardous phenomena, and determine the avoidance or circumnavigation route around the storm and arrange for and accept the approved course deviation(s) from the air traffic controller.

In the terminal area, opportunity for the pilot to avoid the storm using the airborne weather radar information is somewhat more limited due to the decreased amount of available airspace, and other duties associated with approach to, or departure from, the airport.

The performance characteristics of some of today's airborne weather radars are compared, in Table 2, with the WSR-57 weather radar.

Table 2.--Airborne weather radar and WSR-57 technical characteristics

	Raytheon WSR-57	Bendix RDR-1E	Bendix RDR-1F
Wave Length	10cm	3.2cm	3.2cm
Peak Power	410kw	50kW	65kW
Antenna Gain	38.3dB	34.5dB	33dB
Pulse Width (usec)	4usec	5.5usec	5.0usec
Minimum Detectable Signal	-108dBm	-106.5dBm	-108dBm
PRF	164/545pps	200pps	200/400pps
Display Range	250nm	300nm	50/150/300nm
Horizontal Beam Width (Half Power)	2.2°	3°	3°
Vertical Beam Width 0	2.2°	3°	3°
Polarization	Linear	Linear	Linear
Antenna rmp	3	15	15
Peak Power in First Side Lobe	--	--	--
Azimuth	-20dB	-18dB	-23dB
Elevation	-20dB	-17dB	-23dB

Satellites and Others

General

Detection, location, and tracking of certain types of hazardous weather is carried out operationally by systems other than weather radar.

Environmental satellites are the prime detection systems for hurricanes, typhoons, and other disturbances in the tropical and data-sparse regions of the globe and serve as data sources for areas beyond weather radar coverage.

Specialized weather reconnaissance of tropical storms provides detailed in situ measurements of essential physical characteristics to aid in prediction of location and intensity of these disturbances.

A specialized network of direction-finding devices is used to detect and locate lightning discharges as an aid in fighting lightning-caused forest fires.

The satellite and direction finding systems are described below to outline and highlight their unique system capabilities as well as their interface with weather radar systems.

Satellite Systems

The National Earth Satellite Service (NESS) observing program consists of polar-orbiting and geostationary satellites. DOC, through NESS, is the agency responsible for a national operational environmental satellite system. The Department is charged with operating and improving the system to meet the common requirements of all Federal agencies. The objectives of the operational system are:

- o Provide global imagery of the Earth and its environment on a regular basis, day and night, including direct readout to local ground stations within radio range of the satellite.
- o Obtain quantitative environmental data on a global basis, such as temperature, moisture, winds, radiation flux, and solar energetic particle flux, for use in numerical analysis and prediction programs.
- o Obtain near-continuous observations of the Earth and its environment, collect data from remote observing platforms including automatic weather stations, balloons, aircraft, ships, buoys, and river and tidal stations, and broadcast weather data to remote locations.
- o Improve monitoring and prediction of the atmospheric, oceanic, and space environments by developing applications of satellite information.

The TIROS N system of environmental polar-orbiting satellites focuses on increasing the accuracy of weather forecasting by providing quantitative data required for improved numerical models. It provides improved temperature soundings and microwave channels to

facilitate sounding retrieval in cloudy areas. It provides advanced multichannel images and will carry a new data collection and platform location system.

The geostationary satellites, GOES 2 and GOES 3, provide repetitive viewing of the development and movement of destructive weather systems, such as thunderstorms, hurricanes, and major midlatitude storms over much of North and South America and adjacent oceans. The principal instrument is the Visible and Infrared Spin Scan Radiometer (VISSR). The VISSR provides near-continuous cloud viewing with resolutions of 1, 2, 4, and 8 km in the visible wavelengths and 8 km in the infrared wavelength. Full Earth disc pictures are available at 30-minute intervals throughout the day and night; partial disc pictures can be obtained at more frequent intervals to meet special requirements such as viewing development and movement of severe storms. The GOES Data Collection System is used to collect and relay environmental data observed by remotely located sensing platforms, such as automatic weather stations, buoys, and river and tide gages. Table 3 shows the planned launch schedule for polar-orbiting and geostationary satellites by DOC.

The Defense Meteorological Satellite Program (DMSP), an operational satellite system managed by the Air Force for DOD, supports military requirements worldwide. DMSP provides specialized meteorological data required by DOD and provides maximum responsiveness to the military decisionmaker. DMSP provides visual and infrared (IR) images of the entire globe plus temperature and moisture soundings, auroral electron count, and other specialized meteorological data to Air Force Global Weather Central (AFGWC). It also supplies direct, real-time readout of regional cloud-cover information (visual and IR) to selected military locations around the world.

DMSP consists of two polar-orbiting satellites, each in an approximate 830-km polar, Sun-synchronous orbit with a period of 101 minutes. One satellite has an early morning local Equator-crossing time, the other near noon.

Lightning Direction-Finding Systems

Detection of lightning, including location of the discharge by magnetic detection-finding equipment, has direct application in forest fire detection. Networks of these direction-finding stations are installed in the western United States and Alaska. The U.S. Department of Interior's Bureau of Land Management (BLM) operates these stations as an aid in wildlife management and fire weather forecasting. Fire detection aircraft and sometimes even fire suppression crews are sent directly to those areas where networks show lightning is occurring (Krider et al. 1980).

Table 3.--Projected satellite launch schedule

POLAR-ORBITING SYSTEM (Federal Plan for 1981)			
Satellite Designator	Planned Launch Date	Instruments TIROS N Series	
NOAA B	3QFY80*	AVHRR	Advanced Very High Resolution Radiometer
NOAA C	FY 1981*	TOVS	TIROS Operational Vertical Sounder
NOAA D	FY 1982*	SEM	Space Environmental Monitor
NOAA E	FY 1983*	DCPLS	Data Collection and Platform Location System
NOAA F	FY 1984*		(ARGOS)
NOAA G	FY 1985*		Modified Height Resolution Infrared Sounder
NOAA H	FY 1986*		
NOAA I	FY 1987*	HIRS/2	
GEOSTATIONARY SYSTEM			
Satellite Designator	Planned Launch Date	Instrument	
GOES D	FY 1980*	SEM	Space Environment Monitor
GOES E	FY 1981*	DCS	Data Collection System
GOES F	FY 1983*	VAS	VISSR Atmospheric Sounder (GOES D and subsequent spacecraft)
GOES G	FY 1985*		
GOES H	FY 1986*	VISSR	Visible and Infrared Spin Scan Radiometer

* Launch date depends on performance of prior spacecraft.

Such a system, that detects and locates lightning directly, is desirable in this specific application as some clouds produce much precipitation and little lightning and others produce lightning and little precipitation. However, additional utility of this type of detection system, where available, is limited to a support role to an existing weather radar (O'Malley 1980, Kohl 1980).

SYSTEM ALTERNATIVES

General

Utilizing a systems analysis approach, this report forecasts technology that will be available within the next 5 years and develops scenarios to describe the various alternatives to be considered for the NEXRAD System. The descriptions provide a general understanding of what is comprised in each scenario. This includes: equipment, capability, operational procedures, dissemination, and other significant aspects. Figure 5 depicts the components of a typical NEXRAD unit. The scenarios include the range of technically feasible options including: an integrated Doppler radar program, a mix of Doppler and non-Doppler radars, and an alternative that would maintain current system capabilities at an acceptable performance level.

Weather Radar Scenarios

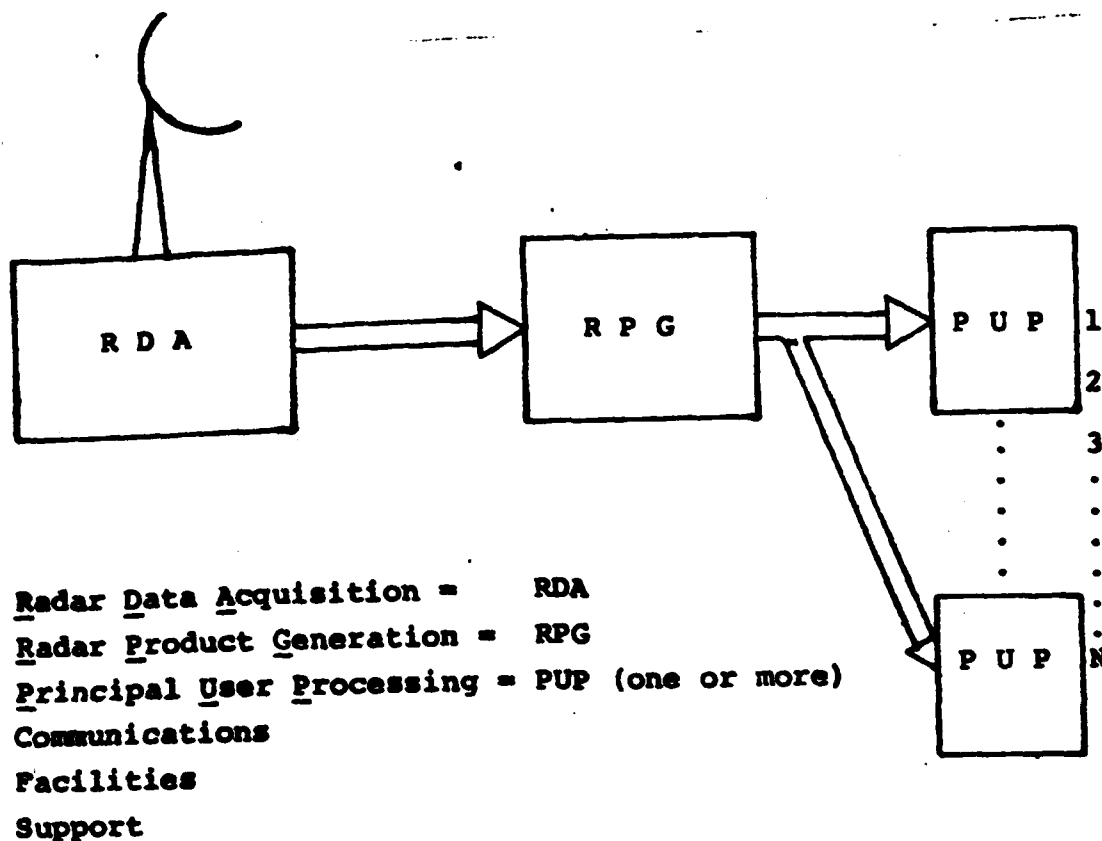
A set of seven weather radar system scenarios has been defined for evaluation and comparison. The first three of these scenarios postulate networks of 140 Doppler weather radars. Two scenarios are mixed networks with 95 Doppler weather radars for locations where there is a relatively high risk of hazardous weather and 45 non-Doppler radars for regions of lower risk. Scenarios 6 and 7 are weather radar networks that do not utilize Doppler weather radars in the network.

Three types of Doppler weather radars are defined that comprise the first three scenarios. The Type I Doppler radar, in Scenario 1, is a five-beam, two-frequency system employing five receivers (one for each antenna beam) and two transmitters. This configuration permits full volume scanning to 70,000 feet altitude in 5 minutes. See Appendix E for detailed descriptions.

The Type II Doppler weather radars that comprise Scenario 2 are two-beam systems employing two receivers and a single transmitter. The Type II radar is basically a two-beam version of the Type I radar. Full volume scanning to 70,000 feet altitude is achieved in 6.2 minutes with a rotation rate of 2.4 rpm.

The Type III Doppler weather radars defined for Scenario 3 are single-beam, single transmitter systems of the type described in the Report of the Joint Doppler Operational Project (1979). This configuration, with only a single narrow beam, will require 11.7 minutes for a full volume scan up to 50,000 feet in altitude.

Type IV weather radars are defined as coherent, non-Doppler radars that are identical to the Type III Doppler radar except that the coherent Doppler channel of the receiver is not implemented. The Type IV radar makes up the entire network in Scenario 6. The lack of the Doppler information permits full volume scanning to 50,000 feet in 8.3 minutes. The Type IV radar is readily convertible to the Type III Doppler radar.



NEXRAD Joint Program
 Development
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Figure 5.--Components of a NEXRAD unit.

Scenario 7 is made up of a network of non-Doppler, Type V weather radars. The Type V weather radar is considered a replacement for the aging WSR-57, a modernization utilizing current solid-state technology. Examples of the type V radar are the Raytheon WSR-77 and the Enterprise WSR-748. Measuring reflectivity only, with a 2.2-degree beam, full volume scanning can be accomplished in 5 minutes, with loss in resolution associated with the wider beam.

Scenarios 4 and 5 are weather radar networks that postulate the installation of both Doppler and non-Doppler weather radars. In Scenario 4, the Type II Doppler radar would be installed at 95 relatively high risk locations, with the Type IV coherent, non-Doppler at the 45 low risk locations. In Scenario 5, the Type III Doppler radars at the 95 high risk locations are coupled with the Type IV non-Dopplers at the 45 lower risk locations. More detailed descriptions of the radar types are provided in Appendix E. See also Table 4.

Table 4.--Cost summary--NEXRAD scenarios
(For a total of 140 radars in each scenario).

Scenario No: Costs in Millions									
	1	2	3	4	5	6	7		
Program Management	28	28	28	28	28	18	10		
Program Development									
Validation	24	24	24	30	28	12	8		
Full Scale Development									
Testing-Training	5	5	5	8	6	4	2		
Documentation	5	5	5	8	6	4	2		
Software	14	14	14	18	18	7	6		
Production (Includes Initial Spares)									
Radar Hardware	252	119	98	108	91	84	36		
Processors	98	98	98	67	67	65	60		
Facilities	35	22	20	21	20	17	12		
User Displays	107	107	107	107	107	83	83		
Total: Non-Recurring	\$568	\$422	\$399	\$395	\$371	\$294	\$219		
Operations and Support									
Operations (Personnel)	\$11	\$11	\$11	\$11	\$11	\$11	\$11		
Logistics (Personnel-Spares)	6	6	6	10	9	6	6		
Training	2	2	2	2	2	2	2		
Total: Recurring	\$21	\$21	\$21	\$23	\$22	\$19	\$19		
	Doppler (5-beam)	Doppler (2-beam)	Doppler (Single-beam)	Mixed System 2-beam Dop- pler and Non-Doppler	Mixed System 1-beam Dop- pler and Coherent Non-Doppler	Coherent Non-Doppler	Non-Coherent Non-Doppler		

COST/BENEFITS

Introduction

In an average year, severe weather kills hundreds of people, injures thousands more, and inflicts an enormous amount of property damage. In such a year, the U.S. mainland will experience 2 hurricanes, 600 tornadoes, 600 damaging hailstorms, 100 significant flash floods, 1,000 severe local windstorms, and many winter storms. During any individual year, these averages, particularly with regard to casualties and damages, can be dwarfed by singular disasters. At the same time, it is realized that a large portion of the losses are due to a fraction of the number of storms.

Compiling an adequate summary of property losses, loss of life, injuries, and other costs resulting from hazardous weather events is a difficult task because the data base is weak. There appears to be no single federal agency responsible for systematically maintaining a record of such losses and costs.

The benefit assessment in this report is obtained by comparing the NEXRAD System capability to today's system in terms of improved performance to detect, locate, and track those hazardous weather phenomena that impact the aviation industry, the military, and the general public. In addition, the improved performance of the NEXRAD in probing other atmospheric phenomena is assessed. With reasonable assumptions, the study defines the benefits that will accrue in a 1990 environment highlighting benefits that can be translated into dollar values. The study also identifies benefits that are not translatable to dollar values at this point in time, but are assessable in a subjective fashion.

Costs--General Approach

While there is no systematic summary of property losses, several authors, insurance associations, and the Federal Coordinator for Meteorological Services have made estimates of annual hazardous weather losses.

Although other studies of weather-caused losses have been made in the past, perhaps the most comprehensive is J. C. Thompson's study of potential economic benefits derivable from improved weather forecasting. Thompson estimated our annual national losses due to severe weather at \$12.7 billion, of which some \$5.3 billion were deemed to be avoidable through availability of improved forecasts (1972). Thompson estimates are comparable to Senko's 1963 estimate of \$10 billion included in his unpublished report (1964).

The 1973 "Federal Plan for Meteorological Services and Supporting Research" estimated annual adverse weather losses in the U.S. at \$15 billion, of which \$7 to \$10 billion were considered avoidable given adequate warning of impending adverse weather (OFCM 1973). These

two studies, 1 year apart, are indicative of the variability of the data base with estimates of annual losses varying between \$12.7 and \$15 billion and avoidable loss estimates varying from \$5.3 billion to \$7 to \$10 billion. Regardless of the variability of the data base it is evident from the data collected in this study that the property losses due to hazardous weather are substantial.

In the Thompson study, avoidable losses in various social activity areas were related to the timeliness of forewarning, such as 1 to 5 hours, 6 to 11 hours, 12 to 36 hours, etc. Avoidable losses with improved warnings of 1 to 5 hours were estimated in the range of \$0.83 billion to \$1.5 billion annually.

At the shortest warning interval, 1 to 5 hours, the economic sectors having the largest potential savings (approximately 25 percent), were commercial aviation, electric power, manufacturing, and transportation (rail, highway, and water). For the general public, the potential savings value was approximately 15 percent. NEXRAD, if deployed, would provide the means for issuing earlier, and more accurate warnings, in the 0.1- to 3-hour time frame.

To facilitate the payment of claims and to help property owners restore order in the wake of hurricanes and other perils that produce extensive, widespread damage, the property-liability insurance companies have catastrophe procedures that are put into effect when the total insured loss is expected to exceed \$1 million.

The American Insurance Association (1979) and the Insurance Services Office maintain a record of property damages as a result of catastrophes caused by hazardous weather. These estimates are based on data reported to the American Insurance Association and Insurance Services Office and cover insurance losses only, not total property damage. Weather-related loss payments in 1979, as reported by the property claim services, totaled over \$1.6 billion. This figure includes loss payments of over \$100 million for Hurricane David and approximately three quarters of a billion for Hurricane Frederick. The largest previous catastrophic insurance loss on record resulted from Hurricane "Betsy", which struck Florida, Louisiana, and Mississippi in September 1965, causing insured damage of \$715 million.

The J. H. Wiggins Company of California recently published the results of its work on development of forecasts associated with our most destructive natural hazards. These studies were sponsored by the National Science Foundation and the results published in "Building Losses from Natural Hazards: Yesterday, Today and Tomorrow" (1979). The study projected damages to buildings caused by nine natural disasters. Using the information included in the Wiggins Company report, the projected damages to buildings in 1980 as a result of floods, tornadoes, and hurricanes including storm surge was \$7.1 billion. Table 5, extracted from data in the report, illustrates the Wiggins Company's projection of damages to buildings

Table 5.--J. H. Wiggins projected annualized building losses from floods, hurricanes, and tornadoes under 1980 conditions

Floods	\$2.5	Billion
Hurricane Winds	1.6	
Hurricane Storm Surge	1.0	
Tornadoes	2.0	
Total	\$7.1	Billion

in 1980. These figures are intended to indicate only the projected damage to buildings from these hazardous weather events. No estimate is made concerning what percent of these losses can be mitigated by improved hazardous weather warnings.

The more direct costs of severe weather are loss of life and injuries. As stated, the data base is weak, however, the magnitude of death and injuries can be inferred from the discussion of specific hazards that follows the general discussion of benefits.

FEMA and NRC--The Federal Emergency Management Agency (FEMA) and the National Red Cross (NRC) incur significant costs as a result of weather-related disasters. Table 6 shows the costs incurred by the NRC during fiscal years 1979 and 1980 for disaster services relating to hazardous weather events. A much larger cost for hurricanes is shown in 1980. This is due to Hurricanes David and Frederick, which occurred in calendar year 1979 but are costed in the NRC 1980 fiscal year. The low figure for hurricanes in FY 1979 illustrates the fact that no major hurricanes reached the mainland U.S. during 1978.

FEMA and its predecessor agencies have disbursed over \$3.3 billion dollars from 1953 through 1979 as a result of major disasters. Most of these funds were disbursed for weather-caused losses. In 1979 alone FEMA disbursed over \$300 million for weather-caused disaster losses.

Benefits--General Approach

The benefits that will accrue from NEXRAD are considered in three categories: (1) those that can be quantified in dollars and are associated with hazardous weather phenomena; (2) those that are not quantified and are associated with hazardous weather phenomena; and (3) those that are not quantified and are not related to the occurrence of hazardous weather.

The dollar values derived are an estimated percentage of the cost of a particular hazard (e.g. tornadoes). These percentages are based on reviews of existing literature and discussions with experts. This value is a ratio of the costs saved and/or losses prevented due to the improved weather radar information to the total annual costs resulting from that hazard. See Figure 6. The benefits accrue through a more timely evaluation and/or a more accurate depiction

Table 6.--American Red Cross disaster services

1979*	
Hurricanes	\$ 2,532,000
Tornadoes	2,798,000
Other Storms	486,500
Floods	<u>10,788,000</u>
Total Cost	\$ 16,604,000
1980**	
Hurricanes	\$ 13,894,645
Tornadoes	1,117,918
Other Storms	3,707,890
Floods	<u>5,741,383</u>
Total Cost	\$ 24,461,836

*These costs were incurred by the American Red Cross in rendering aid to victims and do not represent the total costs of the disasters. Based on Fiscal Year July 1 to June 30.

**Through October 1980

and prediction of the onset of the hazard resulting from the improved weather radar capability. In some circumstances, the improved warning service may not result in a reduction of property losses. For example, an improved NEXRAD System could reduce the total number of deaths and injuries due to tornadoes with no reduction in fixed structure loss. However, losses of movable property, such as aircraft, can be reduced with adequate warning.

The basis of the analysis is a comparison of the performance capability of the existing weather radar system (WSR-57) to the relative increased capability that is provided by the proposed alternatives. The analysis concentrated on Radar Types II, III, and IV as defined in Appendix D, and assessed capability to detect, locate, and track nine types of hazardous weather phenomena. These estimates were made from the results of a survey of 21 noted weather radar experts. The details of the survey and a listing of the contributors are in Appendix D together with a selection of unattributed comments. Table 7 summarizes the results of the survey using inputs from the experts who chose to indicate percentage values. Table 7 also shows improvement percentages based on discarding the higher and lower estimates.

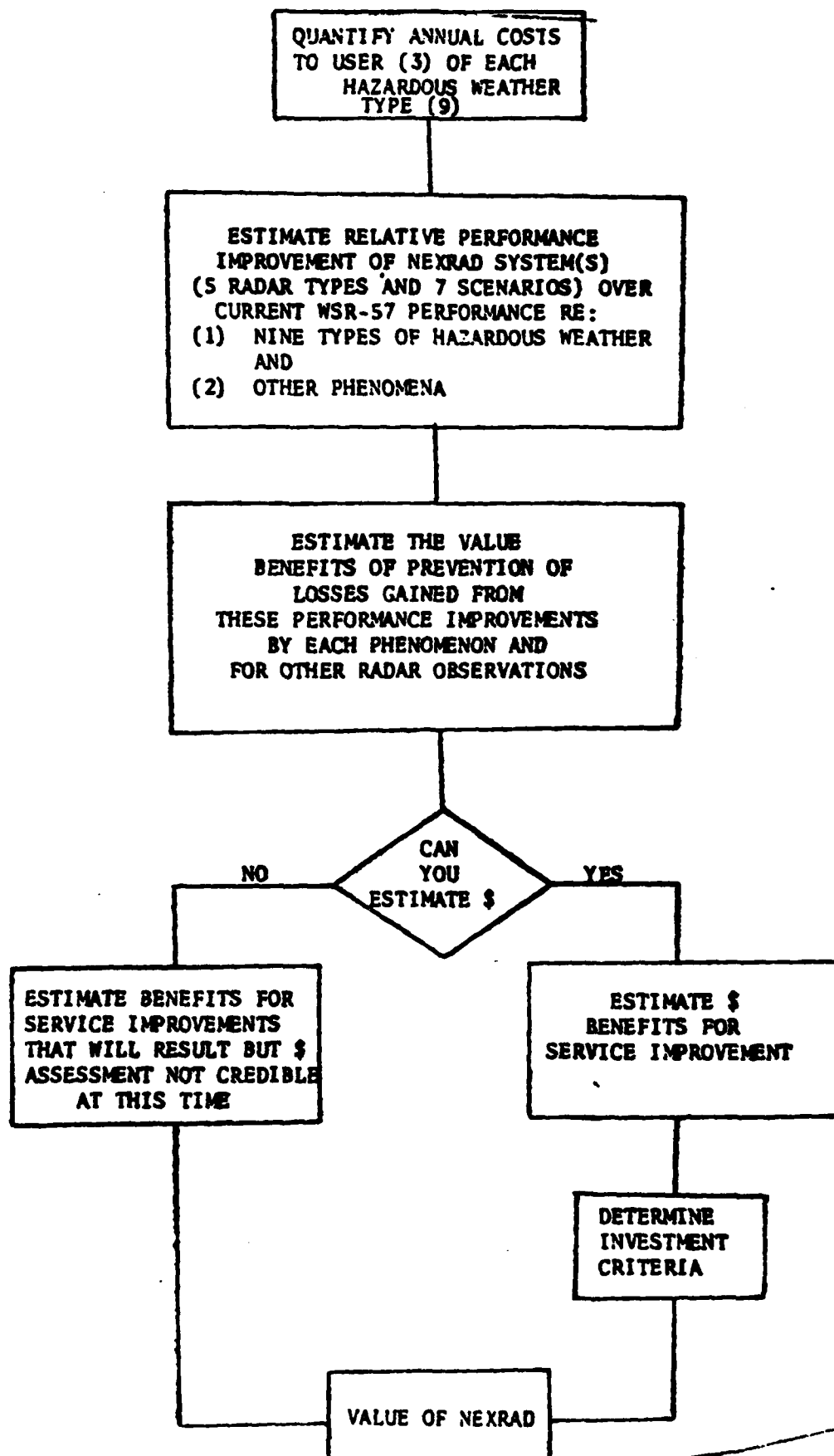


Figure 6.--Method of NEXRAD benefit assessment

Table 7.--Average percentage of improvement in performance of proposed NEXRAD Doppler radar over non-Doppler based on survey from 14 weather radar experts

Type II Doppler vs. Type IV Non-Doppler		
Phenomena	All Respondents (14)	Respondents 2 through 13 Only (Discards Highest and Lowest Estimate)
Tornado	114	71
Turbulence	110*	76
Thunderstorm	50	34
Hail	41	24
Icing	9	7
Flash Flood	33	22
Wind	100	66
Hurricane	49	33
Severe Winter Storm	41*	20

* 13 Responses to these phenomena

With the performance improvements estimated for these phenomena, for which case studies or analogies are described in the literature with acceptable assumptions, benefits in terms of dollar values are derived on a one to one basis with the estimated annual cost of the particular phenomena.

This method of compiling benefits as a percentage of the national costs or losses (costs/losses from available data) does not include benefits that:

(a) accrue as a result of accurate and timely hazard evaluation and prediction, resulting in cancellation of events and activities which would have been disrupted by the unexpected occurrence of the hazard. For example, cancellation of a public concert due to thunderstorm activity. Volume II, Appendix C, Case Study CS-2, describes such a situation.

(b) result from productivity and human activity not being disrupted as a result of more accurate geographic pinpointing of the extent of the hazard and the warning area. Appendix C, Case Study CS-7 provides some estimate of the value of this type of improvement in prediction.

On the other hand, this method does take credit for an unassessable (due to the nature of the data base) percentage of losses which are reported, but that occur during those periods of a day when the capability to respond to a warning based on an adequate NEXRAD evaluation and prediction does not exist. For example, a severe thunderstorm and its destructive winds may occur at an airport at

2:00 a.m. when only security personnel may be on duty. Appendix C, Case Study CS-1, describes such a situation. The extent to which NEXRAD will be able to decrease this type of non-response by improving the credibility of the alert and warnings cannot be estimated. However, such an improvement is expected.

A substantial amount of literature on the evaluation of weather services has appeared in the last two decades, stimulated by the perceived needs of individual national weather services and the World Meteorological Organization. These efforts have served primarily to sketch out the problem, and have not yet produced economic models for standard application. A few case studies, dealing with loss mitigation of particular hazards in specific communities and local areas can serve as suggestive guidelines. However, there are severe limitations that preclude their rigorous application to other phenomena and locations. Among these limitations are that the relationship between increased warning time and loss avoidance is not well known, and information on the efficiency of the response to warnings is not readily available.

In each of the hazardous weather events, e.g., tornadoes, hurricanes, etc., it is assumed that an effective warning system will be in operation at the same time that a more effective weather radar system is introduced. Further it is assumed in the case of these weather events, that effective preparedness activities have been underway. (See Federal Plan for Meteorological Services for FY 1974).

The combination of an adequate warning system coupled with an effective dissemination system in addition to timely response by the affected community has already produced significant cost avoidance in relation to hazardous weather. Table 8 illustrates the complementary input of timely and accurate warning plus community preparedness.

Table 8.--Severe weather warning and community preparedness

Condition	Hurricane	Tornado
No or Poor Warning and Preparedness	Galveston, Texas--1900 6,000 Deaths	Tristate--March 1925 689 Deaths
Timely and Accurate 1965 Warning Only	Audrey--June 1957 526 Deaths (Little evacuation)	Palm Sunday--April 272 Deaths
Timely and Accurate Warnings and Community Preparedness	Celia--August 1971 30,000 Evacuated 13 Deaths	Topeka--June 1966 17 Deaths

In terms of warning time, a 24-hour forecast for a hurricane land-fall is considered a most effective warning time, although subsequent "fine tuning" of the intensity and location of the associated hazardous weather can provide additional benefits. On the other hand, a tornado warning of 1 to 30 minutes may be of considerable value in saving lives.

Thus, benefit can be accrued by an improvement in those warning times that are effective in enhancing safety and are dependent in a large part on the type of hazardous phenomena. The performance improvement of a dual 1-degree Doppler weather radar over a single 1-degree beam non-Doppler radar is appreciable for certain hazardous phenomena and less useful for others. Figure 7 illustrates the percentage improvement in performance of proposed NEXRAD Doppler Weather Radar over Non-Doppler Weather Radar based on survey data from weather radar experts.

Expected Benefits--A comparison of the capabilities of non-Doppler and Doppler weather radar to detect, measure, and evaluate the physical characteristics of the various hazardous weather phenomena is necessary in assessing the benefits from the two types of weather radar. The relative values of these benefit assessments will form the basis for analyzing various system configurations--full Doppler, vs. non-Doppler, vs. a mixed system of Doppler and non-Doppler.

Appendix B, "Doppler Radar--Concepts and Some Experimental Results," provides some additional background on results from recent work on Doppler weather radars as well as a brief discussion of the theory of weather radar.

The Joint Doppler Operational Project (JDOP) (NOAA 1979), conducted during 1976 to 1978, demonstrated the improved capability of Doppler weather radars in: detection and early recognition of tornadoes with 15 to 20 minutes of lead time; recognition of tornadic-storms separated from non-tornadic storms; improved precise location of storm signatures; and significant reduction in the false alarm rate of tornado warnings. This test of Doppler radars in a real-time environment provided "real-world" evidence of Doppler capability in detection and evaluation of tornadoes and thunderstorms. Comparable testing of the unique capability of Doppler radar to detect and evaluate the other forms of hazardous weather--severe winter storms, icing, flash floods, hurricanes, and turbulence has not yet been accomplished. However, research activities provide indications of the unique capabilities of Doppler to decipher the different physical characteristics of these other forms of hazardous weather and to provide improved detection capability for most such phenomena.

Benefits Associated With Both Types of Radars--A significant improvement in data handling over today's analog methods is planned for NEXRAD. The use of digital techniques will allow on-site processing of basic data and the preparation of derived and interpreted

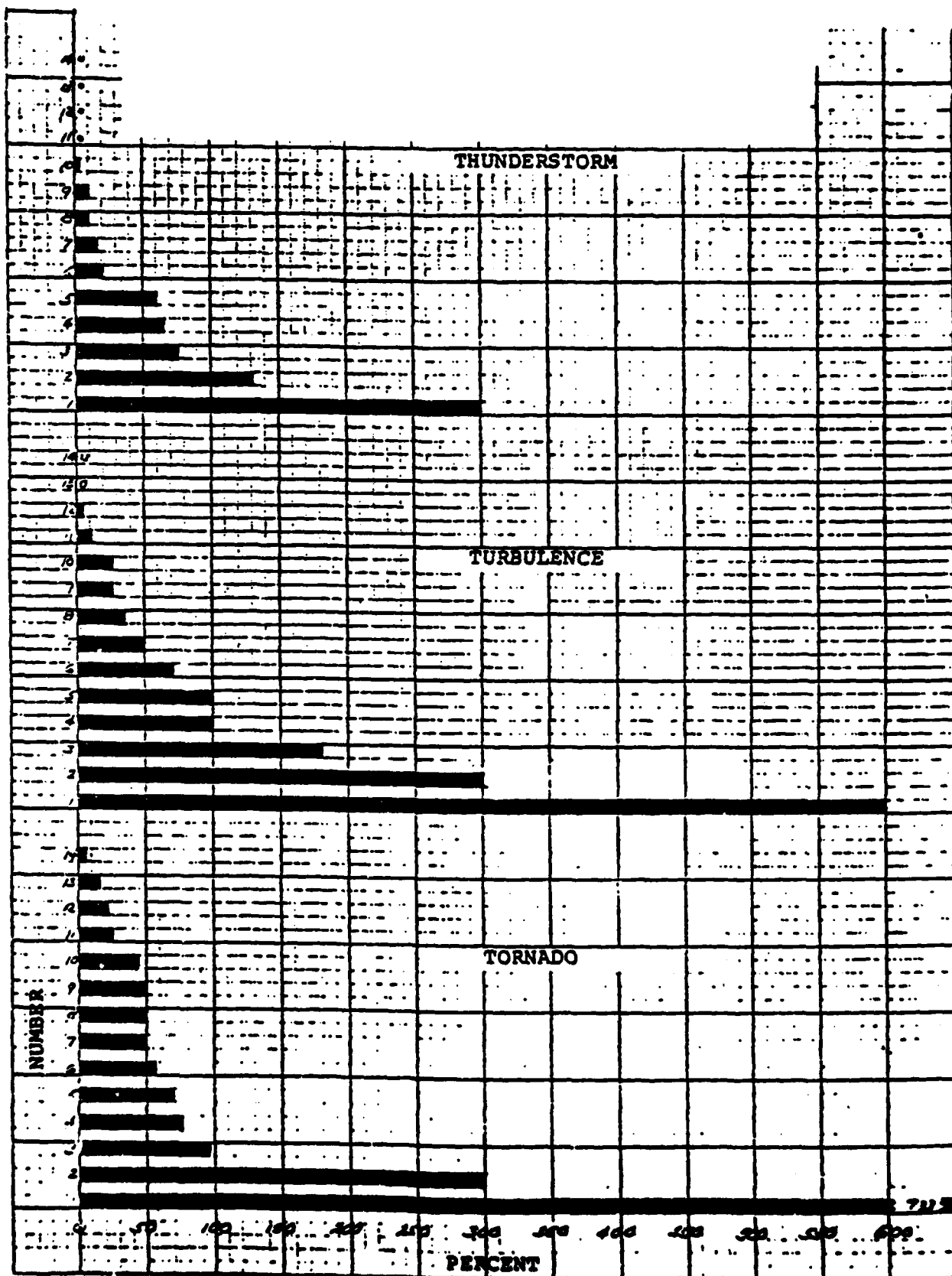


Figure 7.--Percentage of improvement in performance of proposed NEXRAD Doppler radar over non-Doppler based on survey from 14 weather experts Type II Doppler vs. Type IV non-Doppler

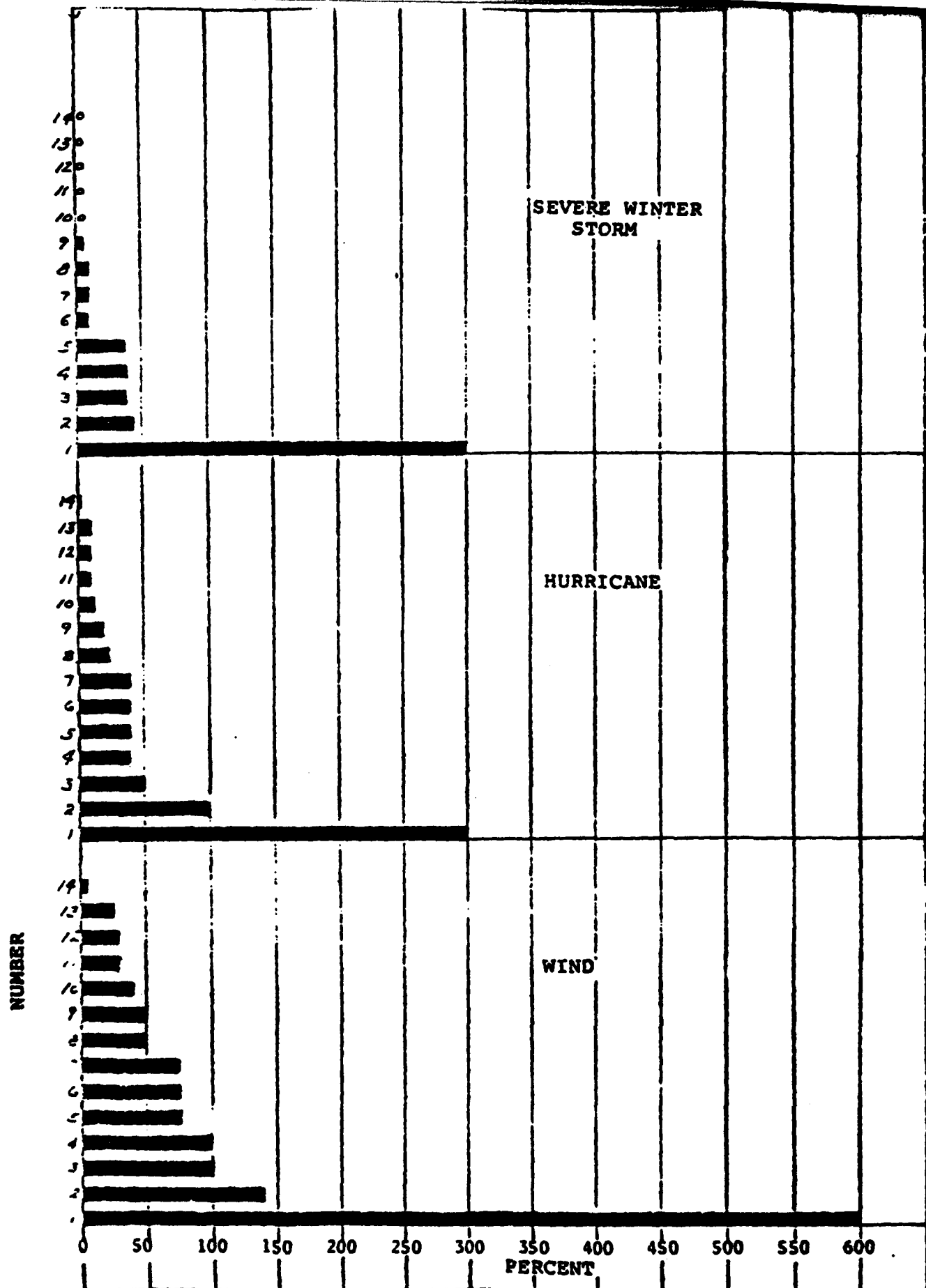


Figure 7.--Continued

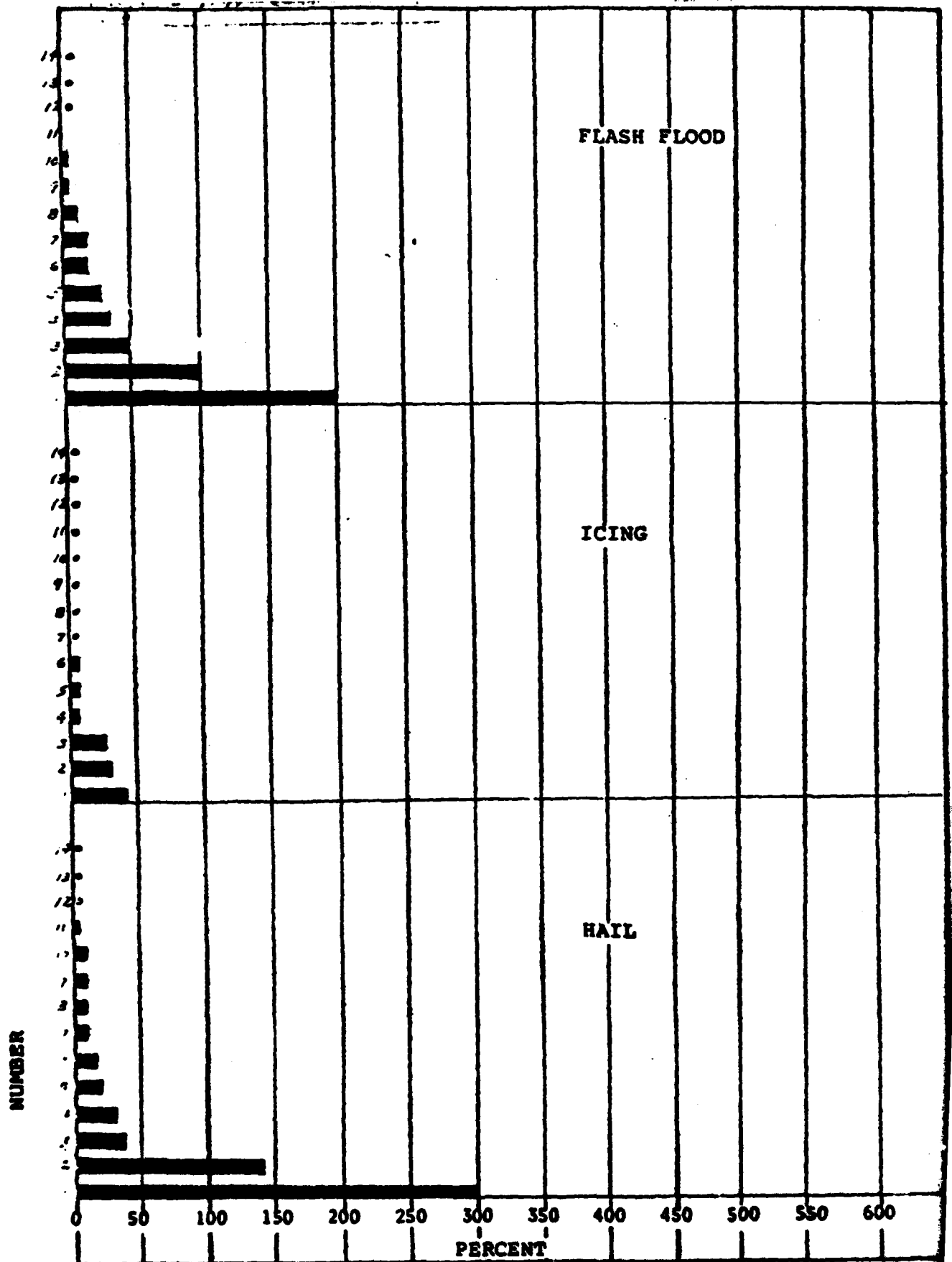


Figure 7.--Continued
35

information for distribution over high-speed circuits. This enhancement will improve the availability of non-Doppler weather radar products, as well as the unique Doppler radar products. In many instances, this increase in capability alone will improve the hazard warning time and provide a significant benefit--not only by making data more timely to the user, but also by making the derived data more readily available to more users. Table 9, submitted by one of the weather radar experts, succinctly summarizes the improvements expected from the NEXRAD deployment due to specified radar characteristics.

In some instances, the existing WSR-57's have been out of operation during hazardous weather events due to maintenance and operational problems. For example, the Athens, Georgia WSR-57 was inoperative on November 6, 1977, between 1:09 a.m. and 1:51 a.m. when heavy precipitation occurred over Western North Carolina (Haggard 1980). This resulted in significantly degraded warning capabilities. Present system availability is between 85 percent and 86 percent (OFCM 1979). The design goal of over 95 percent availability of the NEXRAD System will be an additional asset and contribute to the benefits to accumulate to NEXRAD.

Cost/Benefits Related to Specific Hazards

Notwithstanding the information presented previously, there is a significant amount of data relating directly to losses associated with certain types of severe weather. Although these data come from a variety of sources and are by no means complete, the magnitude of the losses associated with catastrophic weather can be established. In this section we will attempt to identify the documented significant losses, both lives and property, attributable to various hazardous weather events.

The performance improvements of the proposed NEXRAD radars are summarized by the types of hazardous phenomena. These improvements are then associated with the cost and loss values of the phenomena. A rationale for the reduction in losses (benefits accrued) is given. In many instances, benefits associated with the various radar types and not necessarily directly related to hazardous phenomena are described and potential applications described.

Floods and Flash Floods

Costs--In 1966 the Task Force on Federal Flood Control (1966) reported to the 89th Congress that the annual flood damage in the U.S. was roughly estimated to average \$1.0 billion. During the decade of the 1970's, in spite of significant expenditures on flood control, the estimate of damages exceeded that \$1.0 billion figure.

Table 9.--Improvements expected due to NEXRAD deployment

Phenomenon	Digital Processing of Reflectivity Data	High Spatial Resolution (1° beam vs. 2°)	Rapid Update Rate (6 min. vs. 12 min.)	Expanded Vertical Coverage (70kft vs. 50kft)	Measurement of Motion in Radial Direction
Tornadoes	Uncertain	Some	Significant	Slight	Great
Turbulence	----- u n c e r t a i n -----				
Rail	Significant	Significant	Significant	Some	Doubtful
Icing	Slight	Slight	None	None	None
Flash Flood	Great	Significant	Some	None	None
Wind	Slight	Slight	Slight	None	Great
Hurricane	Significant	Some	Doubtful	Significant	Great
Severe Winter Storms	Significant	Significant	Slight	None	Great

There is also a large toll in human life, even though a high degree of flood protection has been provided. During the period 1955 to 1969, the loss of life in the United States attributed to floods averaged approximately 83 per year. However, since 1968, the average annual death toll from floods has risen to approximately 200. Many of these deaths, as well as much of the property damage, is attributable to flash floods.

Flash floods now rank near the top of the list of killers among weather-related disasters. Deaths from flash floods during the 1970's nearly tripled the death rate of the 1940's.

The National Weather Service defines flash floods as floods that follow within a few hours of heavy or excessive rain, dam or levee failure, or sudden release of water impounded by an ice jam. Due to the short warning time involved, the NWS flood forecasting procedures used on large streams cannot respond fast enough.

Since 1971 more than 1,000 significant flash floods have occurred. No state has been spared at least one flash flood. The Rapid City flood of 1972 with 236 deaths and the Big Thompson Canyon Flood of 1976 with 139 deaths highlight the potential for flash flood disaster in the U.S. The Federal Emergency Management Agency (FEMA) states that approximately 85 percent of all Presidential declarations of major disasters are associated with floods and flash floods.

The Statistical Abstract of the U.S. 100th Edition, 1979, provides the information shown in Table 10 on deaths and property losses attributable to floods in the U.S. from 1946 to 1977 with specific numbers for 1971 through 1977. The U.S. Water Resources Council predicts that flood damages will reach \$25 billion annually by the year 2000 unless flood plain management is improved.

Table 10.--Flood deaths and property losses 1946 to 1977
(including flash floods)

	1946- 1955	1956- 1965	1966- 1975	1971	1972	1973	1974	1975	1976	1977
Lives Lost	808	557	1,528	74	540	105	121	114	187	212
Property Loss (million dollars)	3,350	2,721	10,225	288	3,449	859	576	1,051	1,000	1,393

Source: Statistical Abstract of the U.S. - 100th Edition, 1979

Analyzing cost avoidance in the case of floods is much more complicated than either tornadoes or hurricanes. While both the detection and forecasting of weather phenomena that cause flooding, including the most dangerous flash flood, are vitally important to the losses both of property and lives, much more is needed in the way of community education, flood plain control, etc.

However, a more efficient detection system that can determine the amount of precipitation falling over a specific land area can significantly improve the effectiveness as well as timeliness of a flood warning. An upgraded radar network would be of lifesaving usefulness by alerting the forecaster to the potential of a flash flood.

Benefits--Common sense suggests that people in the path of floods should be warned so that they may take action to protect their lives and property. Over 20,000 populated areas in the United States are subject to some degree of flooding and several thousand of these communities would benefit greatly by some type of local flood warning program. Only approximately 600 communities currently have such programs (Owen 1980).

The concept of a local flood warning program is straightforward. Rainfall amounts and/or stream levels upstream of the area to be protected are measured and the information is used to predict downstream flows. If the predicted flows are sufficient to cause flooding, appropriate warnings are then issued to the public in the affected area and to officials responsible for taking or directing protective action.

The overall purpose of a flood warning program and the preparedness actions that are enabled by early warning is to reduce the impact of flooding. The principal ways of accomplishing that purpose are by improving safety, reducing property damage losses, and reducing economic losses other than property damage. Tables 11, 12, and 13 (Owen 1980) list some of the ways in which flood warning programs and related preparedness actions may contribute to safety and loss reduction. The extent to which communities can secure the types of benefits cited in Tables 11 through 13 depends largely on the length of warning time that is made available by their flood warning system and the nature of response actions that are pre-planned.

NEXRAD Performance--The addition of digital processing and improved resolution in the horizontal and vertical of the proposed NEXRAD radars are important factors in achieving a 45 to 75 percent improvement in performance over today's radars. Many of the radar experts suggest (Appendix D--Flash Floods) use of dual-polarization as an additional method of further improving the performance in measuring rainfall and rainfall rates over intensity measurements alone.

Table 11.--Potential benefits of flood warning programs and preparedness actions for safety

-
- Evacuation of hazardous areas prior to flooding
 - Early alerts and assistance to invalids or the handicapped
 - Basis for deciding the opening and closing of schools, and release of employees
 - Timely traffic controls to prevent hazardous travel and facilitate evacuation
 - Deployment of personnel and equipment to assure continued medical, fire, police, and other services
 - Emergency management of utilities to avoid fire and explosion
 - Protection of water and sewage treatment facilities to minimize public health problems
-

Table 12.--Potential benefits of flood warning programs and preparedness actions for reduction of property damage

-
- Movement out of the flood plain of mobile equipment, and other movable valuable items
 - Protection of fixed equipment by disconnection of utilities, greasing, wrapping, etc.
 - Protection of structures by sandbagging, anchoring, and other means
-

The estimated performance improvement between Doppler and non-Doppler is depicted in Figure 8 for Flash Floods.

Radar Types II and III are Doppler radars; Type IV is non-Doppler. See Appendix E for more details on these radars. The introduction of the NEXRAD system portends other applications in improving precipitation accumulation measurements for hydrological and agricultural purposes. Research into the morphology of flood producing storms and data processing capabilities may ultimately lead to identification of structure and flow characteristics that will further enhance these applications.

Potential Benefits--In his paper presented to the Second Conference on Flash Floods, Atlanta, Georgia, March 18 to 20, 1980, H. James Owen detailed the concerns of local officials concerning flood warning programs. Tables 11, 12, and 13, on the potential benefits accruing from an effective flood warning system for safety, reduction of property damage, and reduction of losses other than property damage, are based on the information presented in that paper.

Table 13.--Potential benefits of flood warning programs and preparedness actions for reduction of losses other than property damage

-
- Orderly shutdown of production facilities or modifications to continue operation
 - Faster return to normal operations
 - Prevention of reductions in property value and reductions in tax revenue
 - Reduced costs due to fire, explosion, contamination of water supplies, sewage spills
 - Reduced needs for overtime of employees
 - Elimination of costs for unnecessary precautions
 - Reduced costs for emergency shelter, care, and public assistance
 - Reduced risk of liability for injury or deaths in public and private facilities
 - Reduced costs for flood insurance
-

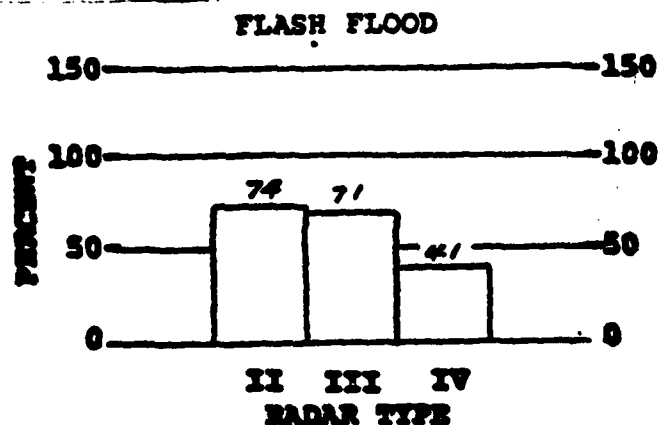


Figure 8.--Average percent improvement of radar type over WSR-57 from 14 responses (all data included).

Although the above benefits apply to more than flooding from flash floods, any improvement in warning time and in accuracy of prediction resulting from NEXRAD radar could make a significant impact in reducing loss of life and property. As it is difficult, if not impossible to partition losses due to flash floods from all floods, we have chosen not to attempt it. Benefits thus expressed represent an estimate for both phenomena.

J. W. Wilson and E. A. Brandes (1979) in their excellent article, "Radar Measurement of Rainfall - A Summary", conclude:

"With reasonable efforts, radar measurements (without gage adjustments) should be within a factor of two of the true rainfall about 75 percent of the time. While this accuracy may not be sufficient for adequate stream flow forecasting, it has important potential for real-time flash flood warning. This was illustrated by the 1977 Johnstown flood disaster. The National Weather Service WSR-57 radar at Pittsburgh was equipped with test equipment to automatically digitize and accumulate rainfall. While the rainfall estimates were low, they did indicate heavy rains were occurring and they could have been very useful in issuing flood warnings. Because heavy rainfalls may frequently be underestimated, the forecaster should take action to verify the radar estimates before they indicate rainfall amounts considered necessary for flooding."

R. E. Saffle and D. R. Greene (1978) in "The Role of Radar in the Flash Flood Watch Warning System: Johnstown Examined", state:

"Although radar underestimated the maximum rainfall in comparison with rain gage measurements, radar estimates gave excellent definition of the time and space distributions of the rainfall and indicated several points of very heavy accumulations. Further, radar rainfall estimates were the only available real-time source of data that gave an objective indication of the flood potential of this event. According to the National Disaster Survey Report on Johnstown (NOAA 1977), real-time surface precipitation reports were not available due to the paucity of gages in the area of heavy rain and to communication problems with the gages that were within the area.

With the introduction of the NEXRAD on-site data processing capability and its improved system reliability, a much more effective integration of rainfall over time and area will be available for use by the flood forecaster. Additionally, the improvement in resolution (1° beam from 2° beam) will improve the credibility of the data and provide a finer spatial resolution of the gridded data. See Table 9.

The results of a demonstration of the real-time capabilities of a radar-man system are summarized by F. A. Huff (et al. 1980):

"Preliminary results from a storm on 30 July 1979 suggest that for such heavier, or hydrologically significant, rains, the system was able to monitor areal rainfall averages to within 13 percent of the total storm rainfall. Further, the average error of the 30-minute accumulated storm rainfall amounts greater than 2 mm ranged from 13 to 20 percent. The radar-man forecast technique was able to predict the onset of precipitation within 30 minutes. The 30-minute updated forecasts of urban rain amounts for 30, 60, and 120 minutes ahead had average forecast errors which ranged from 3 to 5 mm. No adjustments had to be made to the radar-indicated rainfall amounts, and all estimates were based on the climatically-derived CHAP Z-R relation. However, preliminary analysis of other storms indicates the necessity for adjusting the radar-indicated rainfall values for both monitoring and forecasting purposes. Results from the demonstration stress the need to employ skilled operators, including an experienced radar meteorologist, to effectively utilize radar as a heavy rainfall prediction tool."

If we assume a quicker availability of the integrated precipitation data to the forecaster, together with a reduction in grid size from today's Manually Digitized Radar data of 20 n mi and from the D-Radex 3 n mi by 5 n mi, and assume that the gains in time and in spatial resolution are passed ultimately to the user, we can make some estimates of the value of a 1- to 2-hour sooner warning. We can also estimate the value of the improved resolution in improving the credibility of the forecast and the response to the forecast, and the percentage of the avoidable loss of life, property, and other flood associated actions that can be credited to the operation of NEXRAD.

J. Nibler (1980), in a paper presented to the 2nd Conference on Flash Floods, March 1980, approaches the time value question in "Time Characteristics of Flood Warning Systems"; the article summary states:

"Nature imposes the time constraint within which a flood warning system must operate. The relationship between this constraint and the time characteristics of the warning system will determine the warning lead time. It is the primary objective of the warning system to provide a warning lead time comparable to the preparation time required by the flood prone location."

If the location is prone to flash flooding the warning lead time may be maximized by two methods: first, choosing a causal event further back in the chain of events that produces the flash flooding, and second, selecting warning system components that have small time characteristics. The first method reduces the reliability of the system and the second increases cost. If neither of the methods is practical, it may be necessary to accept a shorter preparation

time, but this will decrease the usefulness of the warning. Thus the optimal flash flood warning system will be a compromise between warning reliability, warning usefulness and economics."

The percentage of preventable costs and losses by the NEXRAD improvement in flash flood warning requires estimation of the value of goods and chattels that could be saved by action taken on receipt of the flood warning together with data on the percent damage avoided with emergency actions up to a certain flood stage as well as an estimation of lives saved.

Weather radar with its detailed real time measurement capabilities and scope for quantitative forecasting is most likely to provide the degree of lead time required if maximum preventative action is to be taken at any point. Insufficient information is available to separate out in analytical detail the extent of improvement due to radar as the information must be fed to some flow predicting model for use by the forecaster (R. B. Bussel et al. 1978).

However, the role of weather radar in today's system is described in the National Flash Flood Program Development Plan FY 1979 to 1984, published by NOAA (1978). The following (Table 14) is extracted from that report.

Table 14.--Scales appropriate to the hydrometeorological service problem for flash floods

Name	Averaging times, sizes	Peak intensity sizes	Duration* of concern
Large (L)	6 hours ₂ (160 km) ²	(40 km) ²	24 hours
Medium (M)	3 hours ₂ (80 km) ²	(20 km) ²	12 hours
Small (S)	1 hour ₂ (40 km) ²	(5 km) ²	3 hours
Cumulus (C)	15 minutes ₂ (10 km) ²	(2 km) ²	1 hour

*Periods are before and after the onset of heavy precipitation.

The potential improvement over today's radar in flash flood forecasting through the operation of NEXRAD is greatest for the medium through cumulus scales described above.

H. Tamminga, in the article, "Warning, Evacuation and Rescue of Texas Hill Country Flood Victims" (1980) describes the flash floods

that hit the Texas Hill Country in August 1978. In describing the effect of warning on a sample of 94 survivors but victims of the flood, she states:

"Two of our sample of 94 flood victims were out of town when the flooding occurred, and 11 of the 92 victims in the disaster locale did not have to be evacuated or rescued. 26 respondents left their homes before the flood water hit them so they evacuated before the disaster. 46 of the people we interviewed left their homes while the flooding was in progress, so they evacuated during the disaster. 33 of them made it to safety, and usually found shelter with a relative or friend, or in a temporary shelter provided by a disaster relief agency. However, 13 of the persons who evacuated from their homes during the flooding sought refuge within the flood area, such as in nearby trees, on a neighbor's roof or attic, on a water tower, or on a bowling alley roof. Each of these 13 victims then had to be rescued from that precarious perch above the raging water. The remaining nine victims did not evacuate, but had to be rescued after the floods had placed them in danger.

Our findings, which are summarized below, do support the assumption that victims who received a prior warning were more likely to evacuate their homes before the floods hit them than were those without warning. Those who did not receive a warning were more likely to have been rescued than were those who received several types of warnings. The effect of warning on victim's actions might have been more pronounced if those who received a warning had had more time to react. As it was, a number of our respondents mentioned that they had only a few minutes notice before the water was upon them. Five of them acted immediately upon the warning and left their homes to seek refuge in tree branches or roof tops, from which they later had to be rescued. For these victims, the warning did not arrive in time to allow them to reach safety."

Table 15 illustrates the effect of warnings on evacuation and rescue.

Table 15.--The effect of warnings received on evacuation or rescue

Number of Warnings	Neither	Evacuation Before	Evacuation During	Rescue & Evacuation	Rescue Only	Total Rescued
No Warning (N=48)	6 (12%)	8 (17%)	22 (46%)	8 (17%)	4 (8%)	12 (25%)
1 Warning (N=32)	4 (12%)	12 (38%)	8 (25%)	5 (16%)	3 (9%)	8 (25%)
2 Warnings (N=12)	1 (8%)	6 (50%)	3 (25%)	0	2 (17%)	2 (17%)
Total (N=92)	11 (12%)	26 (28%)	33 (36%)	13 (14%)	9 (10%)	22 (24%)

Although these data reflect reactions by survivors, it is assumed that an earlier warning that allows more time to react would significantly reduce the percentages of people requiring rescue from life-threatening situations as well as significantly reducing the loss of life.

Based on the above, we estimate that the NEXRAD improvement in warning time--of up to 2 hours--will be translated to a reduction in loss of life due to floods, primarily flash floods, of 65 percent to 75 percent, resulting in a savings of from 130 to 150 lives annually, for which we assume a value of \$65 to \$80 million.

The estimate of avoidable property losses that could be prevented by the NEXRAD System carries a degree of uncertainty that requires an estimate of the percentage of avoidable loss within the total property loss. Past research (Mileti 1975) indicates a 5- to 20-percent reduction in loss from warning-dependent, non-structural emergency actions. Effectiveness depends on flood variables, especially stage and onset, and upon the nature of the flood warning system and degree of human responsiveness. An effective warning with at least 1 to 2 hours of lead time and an effective response to warning (assumed here) may enable non-structural emergency action to affect flood damages in the manner indicated in the following (Figure 9).

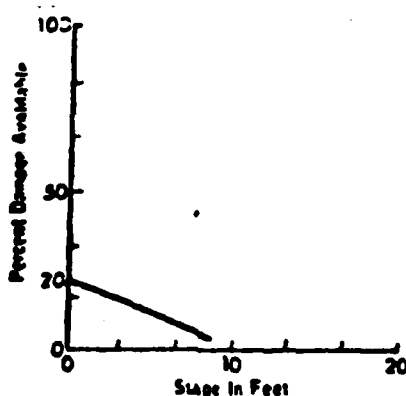


Figure 9.--Percent damage avoided by non-structural emergency actions up to 10-foot stage

Gilbert F. White and J. E. Haas (1975) in a study of the history of flooding in Rapid City, South Dakota, indicate that a 10-percent reduction in damages is achievable with an effective 2-hour warning period.

Based on the aforementioned, we estimate that 15 to 20 percent of the total property losses (mobile and other) can be avoided with the additional 1- to 2-hour warning time, e.g., moving property to a second floor; automobile evacuation, etc. This annual benefit ranges from \$160 to \$200 million.

Thus we estimate that NEXRAD will provide benefits in the range of \$225 to \$280 million in reducing loss of life and property due to floods. It is later shown that this benefit represents one of the more important potential cost savings expected from the installation of a NEXRAD System. It is also clear that this benefit will accrue primarily to the general public rather than to either civil or military aviation.

The following listing summarizes information concerning costs and potential savings for floods. Annual cost includes property loss, deaths, and injuries.

ANNUAL COSTS

<u>Deaths</u>	<u>Injuries</u>	<u>Property</u>	<u>TOTAL</u>
\$109.2M	N/A	\$1.0B	\$1.109B

ANNUAL BENEFITS

\$71 to 82M	N/A	\$150 to 200M	\$221 to 282M
TOTAL POTENTIAL SAVINGS			\$221 to 282M

Tornadoes in the United States

Costs--More than 23,000 tornadoes have struck the United States in the past 51 years, taking a total of more than 7,000 lives. The property damage attributable to these tornadoes produces a staggering total. For the year 1979 alone, the property damage is estimated at more than \$1.0 billion. Table 16 lists the number of tornadoes and deaths attributable during each of the years from 1929 to 1979. This table shows that the number of tornadoes reported per year has been increasing rather regularly. It is probable that this increase reflects more an increasing awareness of the phenomena rather than meteorological factors. To indicate the distribution of tornadoes by region, Table 17 is a listing of tornadoes with deaths and injuries by state for the 5-year period 1974 through 1978. It is interesting to note that only four states, Alaska, Rhode Island, Utah, Vermont, and the District of Columbia have been tornado-free during the last 5 years.

Although we mentioned the property damage caused by tornadoes in 1979, it is not our intention to demonstrate the potential for cost avoidance in terms of property alone as a result of a more adequate and efficient weather radar network. Some aspects of property damage can be alleviated by a longer lead time for tornado warnings, but in the case of fixed property the potential for cost avoidance is minimal. Where that property has some mobility, for example aircraft parked on airports, the potential is indeed significant. The benefits resulting from preventing loss due to tornado of a large number of aircraft assigned to a military base are significant. One such example is described in the benefit section that follows. This potential for cost avoidance is particularly applicable to the military.

The primary cost avoidance in relation to tornadoes is in the area of lives saved and injuries minimized. Tables 18 and 19 (Weather-wise 1980) give an indication of the number of deaths and injuries associated with large outbreaks and with deadly tornadoes. Although we note an increase in the property damage resulting from tornadoes over the last 50 years, it is interesting to note that the deaths attributable to tornadoes during the last 5 years have averaged significantly less than the previous 5-year periods. Obviously, this decrease in the loss of life due to tornadoes must be attributed to an improvement in the current tornado warning system. If we can continue this improvement in providing longer lead times in tornado warnings, it is reasonable to assume that the loss of life will decrease even more dramatically than it has during the 1974 to 1979 five-year period.

Table 16.--Tornadoes in the United States

Year	Tornadoes	Deaths	Year	Tornadoes	Deaths	Year	Tornadoes	Deaths
1929	197	274	1946	106	78	1963	464	31
1930	192	179	1947	165	313	1964	703	73
1931	94	36	1948	183	140	1965	901	296
1932	151	394	1949	249	212	1966	585	99
1933	258	362	1950	199	70	1967	929	114
1934	147	47	1951	272	34	1968	660	131
1935	180	70	1952	236	230	1969	608	66
1936	151	552	1953	442	515	1970	652	72
1937	147	29	1954	550	36	1971	889	156
1938	213	183	1955	595	126	1972	741	27
1939	152	87	1956	503	83	1973	1109	87
1940	124	65	1957	856	191	1974	947	361
1941	118	53	1958	563	66	1975	918	60
1942	167	384	1959	604	58	1976	835	44
1943	152	58	1960	616	47	1977	852	43
1944	169	275	1961	698	51	1978	788	53
1945	121	210	1962	658	28	1979	852	84

Source: United States Department of Commerce--National Oceanic and Atmospheric Administration

Table 17.--Tornadoes by state
(five year totals 1974 to 1978)

State	Tornadoes	Deaths	Injuries
Alabama	147	104	1,350
Alaska	0	0	0
Arizona	20	1	40
Arkansas	125	24	370
California	28	0	6
Colorado	124	0	7
Connecticut	5	0	0
Delaware	10	0	5
District of Columbia	0	0	0
Florida	344	8	346
Georgia	104	26	468
Hawaii	3	0	0
Idaho	2	0	2
Illinois	226	15	328
Indiana	126	52	1,015
Iowa	141	9	200
Kansas	105	25	222
Kentucky	56	73	1,350
Louisiana	187	12	592
Maine	6	0	3
Maryland	29	0	0
Massachusetts	7	0	3
Michigan	148	8	235
Minnesota	88	7	103
Mississippi	149	21	635
Missouri	74	10	158
Montana	31	0	3
Nebraska	246	4	195
Nevada	5	0	0
New Hampshire	6	0	0
New Jersey	8	0	1
New Mexico	22	1	13
New York	30	0	16
North Carolina	122	11	176
North Dakota	158	6	54
Ohio	85	40	1,466
Oklahoma	182	25	501
Oregon	5	0	0
Pennsylvania	75	3	72
Rhode Island	0	0	0
South Carolina	54	7	60
South Dakota	106	0	16
Tennessee	90	48	899
Texas	671	15	246
Utah	0	0	0
Vermont	0	0	0

Table 17.--Continued

State	Tornadoes	Deaths	Injuries
Virginia	56	2	39
Washington	4	0	0
West Virginia	17	1	44
Wisconsin	62	3	113
Wyoming	77	0	3
Puerto Rico	1	0	0
Countrywide Total	4,338*	561	11,355

*Corrected for boundary-crossing tornadoes.

Source: United States Department of Commerce; National Oceanic and Atmospheric Administration

Benefits--Tornadoes cause 143 deaths per year, injure more than 2,200 people each year, and cause more than \$500 million in property losses. In 1979, of the 852 tornadoes (Vigansky 1979), 21 were classified as killer tornadoes causing 84 deaths and 3,077 injuries. The vast majority of tornado deaths and injuries are caused by violent tornadoes with intermediate or long track path lengths--an intermediate track is 3.2 to 32 miles, a long track is 32 miles (Schaefer et al. 1980). These tornadoes last long enough and are of such a nature that the issuance of a timely warning is entirely feasible--the greater the gain in warning time, the greater potential for saving lives. Any improvement in reducing the number of incorrect warnings will further enhance the credibility of the system.

NEXRAD Performance--Experiments, such as the JDOP (NOAA 1979--Interim Report), have demonstrated the improved capability of Doppler weather radars in: detection and early recognition of tornadoes with an average 15 to 20 minutes lead time; recognition of tornadic storms separated from non-tornadic storms; improved precise location of signatures; and significant reduction in the false alarm rate of tornado warnings.

The estimated percentage improvement of the proposed NEXRAD radars over the WSR-57 is shown in Figure 10. Detailed comments on the capabilities of the proposed radar types are listed in Appendix D, Tornadoes.

The difference in the performance capability of the Doppler and the non-Doppler radars for tornadoes is significant and indicates the improvement attributable to Doppler capability. In addition to the Doppler capability the difference in scan time is important, because the faster the scanning mode the earlier, on the average, identification can be made and any minutes gained, due to the short

Table 18.--Five largest tornado outbreaks 1950 to 1978*

Date	Tornadoes	Deaths	Injuries	Area
April 3-4, 1974	148	315	5484	Area between Mississippi River and Appalachian Mountains--Illinois to New York; Mississippi to Virginia
April 11, 1965	51	256	over 1500	Southern Great Lakes; Iowa to Ohio
May 4, 1959	46	0	2 (minor)	Great Plains: Oklahoma to Minnesota and Wisconsin
April 21, 1967	43	58	1068	Central Mississippi Valley to Southern Great Lakes: Missouri to Michigan
January 9-10, 1975	42	11	287	Southern Plains, Lower Ohio Valley and Southeastern states; Texas to Alabama; Oklahoma to Southern Indiana

* Source: National Severe Storms Forecast Center, Tornadoes: When, Where, How Often; Weatherwise, Number 52.

Table 19.--Five deadliest individual tornadoes* 1950 to 1978

Date	Place	Deaths
June 8, 1953	Flint, Michigan	116
May 11, 1953	Waco, Texas	114
June 9, 1953	Worcester, Massachusetts	90
May 25, 1955	Udall, Kansas	80
February 21, 1971	Pugh City, Mississippi	58*

*Source: National Severe Storms Forecast Center, Tornadoes: When, Where, How Often; Weatherwise, Number 52.

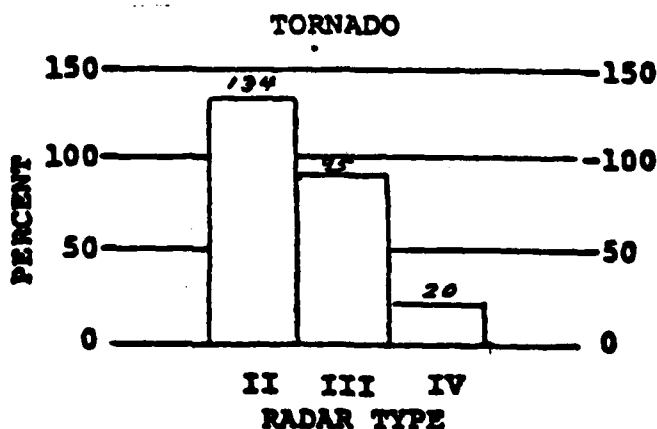


Figure 10.--Average percent improvement of radar type over WSR-57 from 14 responses (all data included)

time available for tornado warnings, are definitely advantageous. The advantage of Type II with a 6.2-minute scan time over the Type III with a 11.7-minute scan time is reflected in Figure 10.

The JDOP (NOAA 1979) indicated the extent to which tornadic storms can be identified as well as the degree of significant reduction in the false alarm rate of tornado warnings. The use of Doppler also improved the precise location of signatures. D. W. Burgess and R. J. Donaldson, Jr. (1979) relate results in separating tornadic storm types. They conclude:

"With respect to tornado warnings, attention should remain on supercell storms where disaster potential is great. All maxi-tornadoes and most of the smaller ones observed by Doppler radar have been preceded by an identifiable mesocyclone, with both warning time and ease of mesocyclone recognition roughly proportional to tornado size and intensity. For these reasons, Doppler radar has great advantage as a warning device."

Potential Benefits--G. F. White and J. Eugene Haas (1975) indicate that:

"Several paradoxes are apparent in the pattern of tornado losses in the United States. First, although the increase in tornado damage to property over the years appears to be proportional to the general economic growth, deaths from tornadoes declined. Second, although the potential for human injury and death from tornadoes appears to be greatest in the Midwest and southern Great Plains, such casualties occur most frequently in the South. Third, although the establishment of the National Severe Weather Warning System in 1953 undoubtedly influenced the declining rate of tornado casualties, this decline had already begun before 1953. Factors that may influence these anomalies in loss patterns are differences in the frequency and severity of tornadoes, urbanization, building construction practices, community preparedness, hospital facilities, warning systems, and distinctive behavior characteristics of individuals."

Although these paradoxes point toward the influence of changes in societal factors, the overwhelming significance of being able to provide 15- to 30-minute advance warning of the occurrence of a major tornado lies in the universal improvement in preventing loss of life and reducing injuries. The additional benefit to be gained from a more than 30-minute alert in preventing movable property loss is significant. K. Glover (1980) describes such an occurrence:

"A severe storm which struck Vance AFB, Oklahoma on 2 May 1979 provides a good example of the operational importance of the kinds of information contained in the 1979 JDOP display product. At 1517 CST, JDOP meteorologists identified a mesocyclone in a storm approximately 180 km to the northwest of the radar and, moreover, the cell track showed the troublesome echo moving toward Vance AFB. The AWS forecaster in Oklahoma City issued his first tornado warning at 1526 CST.

The information transmitted to the AWS forecaster every 6 minutes enabled him to give the people at Vance a continuous and fairly accurate picture of the weather bearing down on their base. Shortly before 1600, the storm spawned a small tornado near Oriente, Oklahoma. At 1613, the high reflectivities in the core of the cell indicated hail, and the mesocyclone circulation was still evident. At 1704, the JDOP forecaster identified a tornado vortex signature in the velocity data, and the strong core reflectivities continued to indicate hail. Contact with Vance personnel was lost just after the 1704 update and was not re-established until after the 1754 update. The continued existence of the mesocyclone and high reflectivities showed that this storm was still quite dangerous; however, the cursor analysis indicated that the mesocyclone center had moved to the east of Vance. Once communications with Vance were resumed, the impact of the frequent and detailed advisories on Vance's operations came to light.

The people at Vance had taken the warnings seriously and acted prudently. They moved their entire fleet of 52 T-38 aircraft into hangars, and all personnel were advised to take shelter in the Base Command Post. A tornado heavily damaged the adjacent town of Lahoma and lifted slightly as it crossed the Base at approximately 1730. The Vance weather station recorded a sharp dip in pressure and peak gusts of 70 knots as the tornado passed nearby. Golfball sized hail was found on the T-38 parking ramps, and baseball sized hail was found in the Base housing area, but no Base personnel were injured, and no T-38 aircraft were damaged."

The value of the aircraft involved in this incident is estimated at 84 million dollars (HQ AWS--Telecon December 19, 1980). In Appendix C, Case Studies CS-3, CS-8, CS-10, CS-14, and CS-15 provide further illustrations of the benefits of advance warnings in reducing both loss of property and lives.

We assume that this increase in warning time of tornado occurrence will be passed without delay through the warning system. CS-18 in Appendix C relates a tornado incident with a 15-minute warning and an effective response system. In these instances, the difference in lives saved and property loss prevented is significant.

The above evidence supports our estimate that the improvement in warning time from a NEXRAD Doppler radar (Type II) will translate into a 75- to 85-percent reduction in loss of life, a potential saving of approximately 100 to 120 lives annually, for savings of \$50 to \$60 million.

If injuries are reduced by a similar amount, this will result in a reduction of injuries from 220 to 330 annually, for a savings of up to \$93 million.

Any estimates of avoidable property losses that would accrue due to an improvement in warning time is highly uncertain--yet the case studies cited are evidence that significant loss prevention is possible. We make a conservative estimate that 5 to 10 percent of the total annual property losses can be avoided with the 20- to 30-minute warning. The potential annual property loss avoidance expected to result from implementation of a NEXRAD network composed of Type II Doppler weather radars is in the range of \$25 to \$50 million.

As is true in the case of floods, the loss data that has been reviewed shows that the major portion of these benefits are expected to accrue to the general public. Although the example cited earlier indicates estimated savings of more than \$80 million to the Air Force due to early warning of an approaching tornado, the overall annual savings to the military and civil aviation are not readily determined from the data base.

The following listing summarizes information concerning costs and potential benefits for tornadoes.

ANNUAL COSTS

<u>Deaths</u>	<u>Injuries</u>	<u>Property</u>	<u>TOTAL</u>
\$78.1M	\$113.6M	\$500M	\$691.6M

ANNUAL BENEFITS

\$58.4 to 62.2M	\$85.2 to 90.9M	\$25 to 50M	\$168 to 203.1M
TOTAL POTENTIAL SAVINGS			\$169 to 203M

Thunderstorms

Costs--In addition to the tornado, which is the most violently destructive hazard associated with thunderstorms, the thunderstorm phenomena is also accompanied by destructive lightning, hail, and high winds. Thunderstorms are a multiple-hazard phenomenon. We have chosen to classify hail, turbulence, and tornadoes as separate hazards, although spawned by thunderstorms. These are discussed separately in this report. The phenomena of lightning, microbursts, downbursts, and gust fronts associated with thunderstorms are included here in the thunderstorm discussion. Other wind phenomena such as boundary layer winds, upper winds, and wind shift lines associated with frontal location are considered under the wind category of phenomena.

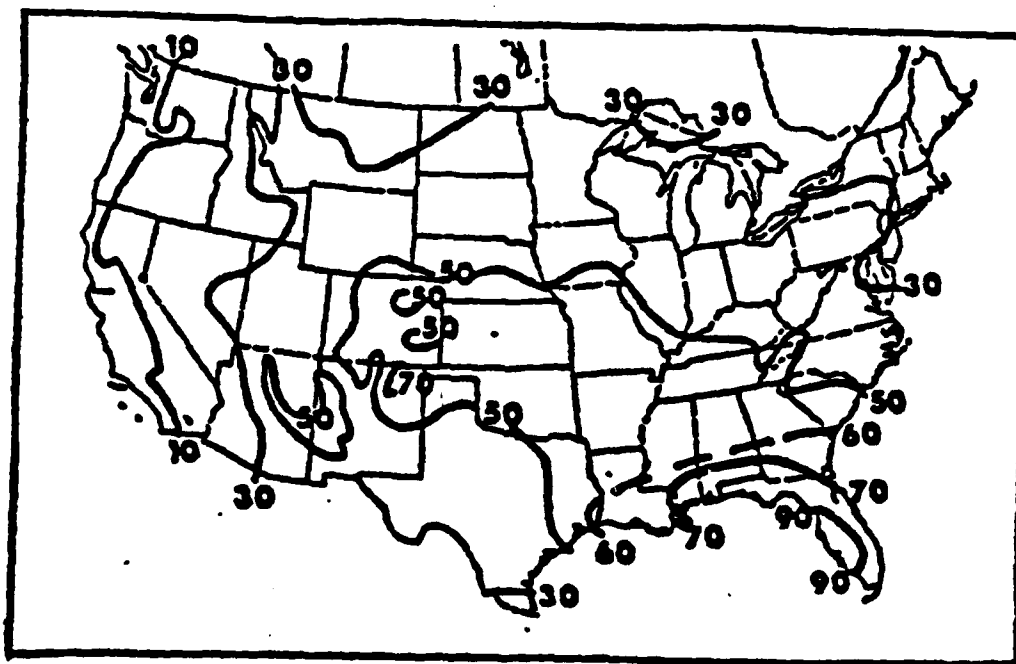
In an average year, lightning probably kills as many people in the U.S. as tornadoes, but these deaths, occurring as single events, do not result in the high public notice associated with tornadoes. Most estimates of lightning-caused deaths average over 100 annually. Mogil (et al. 1977), maintains that annual deaths probably exceed 200 although only about half are reported in any single tabulation. Statistics maintained by NOAA's Environmental Data Information Service (EDIS) for the period of 1959 to 1979 include an annual average of 105 fatalities. Lightning injuries averaged 245 per year over the same period.

Lightning-caused building fires are responsible for at least \$40 million in damage annually. A 1975 study estimates that roughly 10,000 forest fires are caused each year by lightning, resulting in losses in excess of \$50 million annually (White and Haas 1975).

Benefits--Few areas in the United States are free from thunderstorms and their attendant hazards. The map, Figure 11, shows the incidence of thunderstorm days--days on which thunderstorms are observed. Case studies CS-1, CS-2, CS-5, CS-6, CS-9, and CS-12 in Appendix C describe the effects of thunderstorms and the key role that weather radar plays in providing information to reduce the effect of this hazard.

The impact of thunderstorms on aviation includes not only the destruction of aircraft while on the ground, safety of flight, and the operation of aircraft while on the airport, but the operational delay caused by thunderstorms occupying terminal airspace and preventing normal operation into and out of the terminal airport.

For delays greater than 30 minutes, the FAA reports that thunderstorms cause 20 to 30 percent of this type of delay.



(after Baldwin, 1973).

Figure 11.--Mean annual number of days with thunderstorms.

NEXRAD Performance--Today's WSR-57 does a fairly good job of identifying and tracking thunderstorms by recognizing intense reflectivity, rapid development, and high cell tops. The major improvements to result from NEXRAD will come from:

- The digital processing of reflectivity data
- The narrower beam width
- The Doppler capability

The Doppler capability offers the potential of detecting the gust front associated with the cumulonimbus cloud. Since the gust front frequently moves in a direction opposite to the low-level environmental flow (Wilson et al. 1980), a strong radial gradient exists at the leading edge of the gust front. For locating gust fronts, it is often important that the radar have sufficient sensitivity to detect clear air echoes. Doppler processing (Wilson et al. 1979) of the data is helpful since noise discrimination can be improved by 10 dB or more over incoherent processing.

Doppler radars have also demonstrated the ability to distinguish severe thunderstorms from less severe thunderstorms and to locate and identify thunderstorm downbursts through analyses of the velocity field.

Figure 12 depicts the estimated percentage improvement of the proposed NEXRAD radars over the WSR-57.

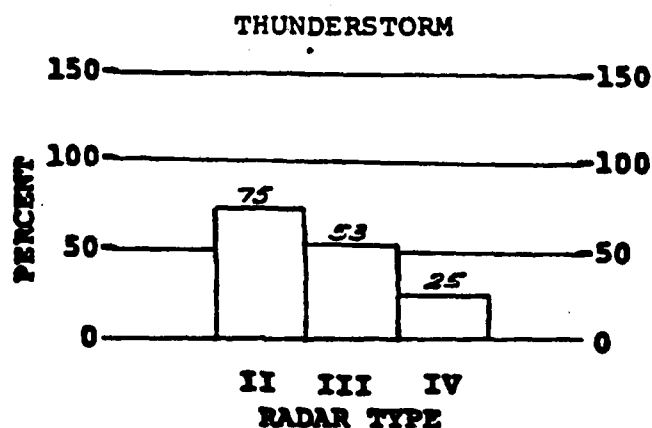


Figure 12.--Average percent improvement of radar type over WSR-57 from 14 responses (all data included).

The 25 to 50 percent improvement of the Doppler radar (Types II and III) over the non-Doppler (Type IV) is related to the Doppler capability to indicate the windfields within the thunderstorm and thus more reliably identify the severity of the storm and detect gust fronts and downbursts. The shorter update rate of the Type II radar over the Type III accounts for the performance improvement credited to the Type II over the Type III.

See Appendix D for the additional comments of the weather radar experts concerning thunderstorms.

Potential Benefits--Today's WSR-57 and other weather radars presently in use to detect and measure thunderstorms, e.g., FPS-77 and ARSR-2, are the backbone for today's alerting and warning system. Case Studies CS-2, CS-10, CS-12, and CS-14 of Appendix C are some examples of the value and benefits from use of today's weather radars. These benefits derive from such actions as: securing movable property (e.g. aircraft), cancellation of scheduled activities, circumnavigating thunderstorms hazardous to flight, postponing aircraft refueling activities, providing alert and warnings to the general public, and planning electrical power changeover to secondary procedures.

As thunderstorm incidence and the accompanying losses are very pervasive, it is not surprising that the improvements in weather radar performance of the NEXRAD in terms of increased warning time, more credible identification of severe thunderstorms, and identification of downbursts and gust fronts translate into additional benefits. Case Studies CS-1, CS-3, CS-5, CS-6, CS-8, CS-9, CS-10,

CS-11, CS-14, and CS-15 in Appendix C are illustrative of circumstances where additional benefits would accrue through the use of a Doppler type NEXRAD radar.

Any reduction in today's delays, diversions, and cancellations of aircraft flight activity due to thunderstorms would provide additional benefits. Unfortunately, in today's air traffic control system there is little or no routine use of thunderstorm data derived from weather radar by the terminal area control system. Thus any differential between today's system and the NEXRAD cannot be assessed readily. However, the potential to reduce operational costs to aircraft operators is appreciable. The savings to the commercial aviation industry by reducing delay costs due to thunderstorms only is more than \$34 million annually. Further details of how this estimate is made is found in the section, "Costs and Benefits Related to Specific Users: Civil Aviation and Military."

The unique capability of a Doppler NEXRAD to identify severe thunderstorms, downbursts and gust fronts would contribute appreciably to the enhancement of safety in aircraft operation, and to reduction in mobile property losses as well as loss of human life. We assume that in addition to the reduction in operational costs to aviation by reducing delay, further benefits in terms of safety improvements, e.g. lives saved, injuries prevented, and aircraft damage avoided, are particularly attributable to the deployment of a NEXRAD Doppler radar system. One estimate of the annual dollar value (1980 dollars) of these safety type benefits is between \$5.8 and \$19.5 million for civilian aviation (Frankel 1980). Further study is indicated in order to reduce the uncertainty of these estimates.

The following listing summarizes information concerning costs and potential savings for thunderstorms.

ANNUAL COSTS

<u>Deaths</u>	<u>Injuries</u>	<u>Operating Costs</u>	<u>TOTAL</u>
N/L	N/L	\$231.5M*	\$231.5M

ANNUAL BENEFITS

\$5.8 to 19.5 M**	\$ 34.7M	\$40.5 to 54.2M
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TOTAL POTENTIAL SAVINGS	\$40.5 to 54.2M
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N/L Not Listed

* Costs to Air Carrier: Operational Loss and Passenger Loss

** Frankel 1980 Study

Hurricanes

Costs--In the last century more than 80 hurricanes have reached the continent of the United States, leaving 3,000 dead (Table 20). In the period between 1900 and 1978, 53 major hurricanes hit the U.S. Gulf and Atlantic coasts. In that time period there were only 8 years in which no hurricane reached the United States, while there were 25 years when two or more hurricanes hit the U.S. coast. Two major hurricanes, David and Frederick, reached the United States in 1979. Major hurricanes are those categorized as having winds in excess of 100 miles per hour and creating storm surges of 9 to 12 feet resulting in extensive damage (Table 21). In that same time period, 1900 to 1978, there were 25 hurricanes that caused more than \$50 million in damage. Hurricane Agnes of 1972 heads this list of costliest hurricanes with \$2.1 billion worth of damage. The combined losses for David and Frederick in 1979 have already exceeded that amount. There were 31 hurricanes causing 25 or more deaths. The deadliest hurricane on record was the one that hit Galveston, Texas in 1900 with an estimated loss of 6,000 lives. The number of hurricanes affecting individual states in the period 1900 to 1978 is shown in Table 22. Figure 13 depicts the percentage of occurrence of hurricane winds in any one year in a specified 50-mile segment of the Eastern U.S. coastline.

As in the case of tornadoes, the primary potential for cost avoidance is in lives saved. However, contrary to the situation involving tornadoes, the hurricane warning system that integrates satellite surveillance, aircraft reconnaissance, and a network of coastal weather radars provides a lead time for protective measures significantly longer than that for tornadoes. It is usually the case that the hurricane warning is provided in terms of hours, while the unit of measurement for tornado warnings is minutes. Much more can be done in terms of personnel evacuation and property protection. A major payoff, of course, would be the potential for narrowing the limit of the warning area prior to landfall. It is assumed that a more effective weather radar network would provide the fine tuning required in hurricane prediction.

Table 23 lists the deadliest hurricanes reaching the United States in the period 1900 to 1978. Major hurricanes are those categorized as 3, 4, and 5. Fifty-three major hurricanes thus categorized hit the U.S. Gulf and Atlantic Coasts between 1900 and 1978. Table 24 lists the costliest hurricanes to hit the United States in the same time period. These ranged in cost from \$52 million to Agnes in 1972, which cost \$2.1 billion. The average cost of these 25 costliest hurricanes was more than \$400 million.

In the decade of the seventies, only three major hurricanes reached the United States. The decreased death totals in recent years may be as much a result of lack of major hurricanes striking vulnerable areas as they are of any foolproof hurricane observing and warning system.

Table 20.--Hurricanes reaching the United States 1929 to 1978

Year Hurricanes Deaths*			Year Hurricanes Deaths*			Year Hurricanes Deaths*		
1929	2	3	1946	1	0	1963	1	11
1930	0	0	1947	3	53	1964	4	49
1931	0	0	1948	3	3	1965	1	75
1932	2	0	1949	2	4	1966	2	54
1933	5	63	1950	3	19	1967	1	18
1934	3	17	1951	0	0	1968	1	9
1935	2	414	1952	1	3	1969	2	256
1936	3	9	1953	2	2	1970	1	11
1937	0	0	1954	3	193	1971	3	8
1938	2	600	1955	3	218	1972	1	121
1939	1	3	1956	1	21	1973	0	5
1940	2	51	1957	1	395	1974	1	1
1941	2	10	1958	0	2	1975	1	21
1942	2	8	1959	3	24	1976	1	9
1943	1	16	1960	2	65	1977	1	0
1944	3	64	1961	1	46	1978	0	35
1945	3	7	1962	0	4			
Totals						81	3,000	

*Deaths include fatalities from high winds of less than hurricane force
Source: United States Department of Commerce--National

Table 21.--Saffir/Simpson hurricane scale ranges

Scale Number	Central Pressure		Winds	Surge	Damage
(category)	(millibars)	(inches)	(miles/hr.)	(feet)	
1	980	28.94	74-95	4-5	Minimal
2	965-979	28.50-28.91	96-110	6-8	Moderate
3	945-964	27.91-28.47	111-130	9-12	Extensive
4	920-944	27.17-27.88	131-155	13-18	Extreme
5	920	27.17	155	18	Catastrophic

Source: Paul J. Herbert and Glenn Taylor, Everything You Always Wanted to Know About Hurricanes, Weatherwise, June 1979.

Table 22.--Number of hurricanes (direct hits) affecting United States and individual states 1900 to 1978 according to Saffir/Simpson hurricane scale

Area	1	2	3	4	5	All	Major Hurricanes (≥ 3)
United States (Texas to Maine)	47	29	38	13	2	129	53
Texas	9	9	7	6	0	31	13
(North)	4	3	2	4	0	13	6
(Central)	2	2	1	1	0	6	2
(South)	3	4	4	1	0	12	5
Louisiana	4	6	6	3	1	20	10
Mississippi	1	1	2	0	1	5	3
Alabama	3	1	3	0	0	7	3
Florida	18	11	15	5	1	50	21
(Northwest)	9	6	5	0	0	20	5
(Northeast)	1	5	0	0	0	6	0
(Southwest)	5	3	5	2	1	16	8
(Southeast)	4	8	7	3	0	22	10
Georgia	1	3	0	0	0	4	0
South Carolina	4	3	2	1*	0	10	3
North Carolina	9	3	6	1*	0	19	7
Virginia	1	1	1*	0	0	3	1*
Maryland	0	1*	0	0	0	1*	0
Delaware	0	0	0	0	0	0	0
New Jersey	1	0	0	0	0	0	0
New York	3	0	4*	0	0	7	4*
Connecticut	2	1*	3*	0	0	6	3*
Rhode Island	0	1*	3*	0	0	4*	3*
Massachusetts	2	1*	2*	0	0	5	2*
New Hampshire	1*	0	0	0	0	1*	0
Maine	4	0	0	0	0	4	0

*Indicates all hurricanes in this category were moving faster than 30 mph

NOTE: State totals will not equal United States totals and Texas and Florida sectional totals will not equal state totals.

Source: Herbert and Taylor, Weatherwise, June 1979 (Updated from Herbert and Taylor, 1975)



Figure 13.--Probability (percentage) of hurricanes (winds exceeding 73 mph, 33 ms-1) or great hurricane (winds in excess of 125 mph, 56 ms-1) occurrence in any one year in a 50-mile (80 km) segment of the U.S. coastline (after Simpson and Lawrence, 1971).

Table 23.--Deadliest hurricanes, United States 1900 to 1978
(25 or more deaths)

Hurricane	Year	Category	Deaths
Texas (Galveston)	1900	4	6000 ¹
Florida (Lake Okeechobee)	1928	4	1936
Florida (Keys/South Texas)	1919	4 ²	600/900
New England	1938	3 ²	600
Florida (Keys)	1935	5	408
AUDREY (Louisiana/Texas)	1957	4 ²	390 ³
Northeast U.S.	1944	3 ²	390 ³
Louisiana (Grand Isle)	1909	4	350
Louisiana (New Orleans)	1915	4	275
Texas (Galveston)	1915	4	275
CAMILLE (Mississippi/Louisiana)	1969	5	256
Florida (Miami)	1926	4	243
DIANA (Northeast U.S.)	1955	1	184
Florida (Southeast)	1906	2	164
Mississippi/Alabama/Pensacola	1906	3	134
AGNES (Florida/Northeast U.S.)	1972	1 ²	122
HAZEL (North and S. Carolina)	1954	4 ²	95
BETSY (Florida/Louisiana)	1965	3 ²	75
CAROL (Northeast U.S.)	1954	3 ²	60
Southeast Florida/La./Miss.	1947	4	51
DONNA (Florida/Eastern U.S.)	1960	4	50
Georgia/North and South Carolina	1940	2	50
CARLA (Texas)	1961	4	46
Texas (Velasco)	1909	3	41
Texas (Freeport)	1932	4	40
South Texas	1933	3	40
HILDA (Louisiana)	1964	3	38
Louisiana (Southwest)	1918	3	34
Florida (Southwest)	1910	3	30
CONNIE (North Carolina)	1955	3	25
Louisiana (Central)	1926	3	25

1 Over 500 of these lost on ships at sea

2 Moving more than 30 miles per hour

3 Some 344 of these lost on ships at sea

Source: Herbert and Taylor, Weatherwise, April 1979

Table 24.--Costliest hurricanes, United States 1900 to 1978
(More than \$50,000,000 damage)

Hurricane	Year	Category	Damage (U.S.)
AGNES (Florida/Northeast U.S.)	1972	1	\$2,100,000,000
CAMILLE (Mississippi/Louisiana)	1969	5	1,420,700,000
BETSY (Florida/Louisiana)	1965	3	1,420,500,000
DIANA (Northeast U.S.)	1955	1	831,700,000 ¹
ELOISE (Northwest Florida)	1975	3 ²	550,000,000
CAROL (Northeast U.S.)	1954	3 ²	461,000,000
CELIA (South Texas)	1970	3	453,000,000
CARLA (Texas)	1961	4	408,000,000
DONNA (Florida/Eastern U.S.)	1960	4 ²	387,000,000
New England	1938	3 ²	306,000,000
HAZEL (North and South Carolina)	1954	4 ²	281,000,000
DORA (Northeast Florida)	1964	2	250,000,000
BEULAH (South Texas)	1967	3	200,000,000
AUDREY (Louisiana/Texas)	1957	4	150,000,000
CARMEN (Louisiana)	1974	3	150,000,000
CLEO (Southeast Florida)	1964	2	128,500,000
HILDA (Louisiana)	1964	3	125,000,000
Florida (Miami and Pensacola)	1926	4	112,000,000
Southeast Florida/Louisiana/ Mississippi	1947	4 ²	110,000,000
Northeast U.S.	1944	3 ²	100,000,000+
BELLE (Northeast U.S.)	1976	1	100,000,000
IONE (North Carolina)	1955	3	88,000,000
Southwest and Northwest Florida	1944	3	63,000,000
Southeast Florida	1945	3	60,000,000
Southeast Florida	1949	3	52,000,000+

1 Includes \$60,000,000 in Puerto Rico

2 Moving more than 30 miles per hour

Source: Herbert and Taylor, Weatherwise, April 1979

Benefits--In the United States, most hurricane damage occurs in a narrow zone along the coast lines of the Atlantic Ocean and the Gulf of Mexico. The lower California coast is less frequently the landfall for a tropical cyclone from the Eastern Pacific Ocean. Today's weather radar system plays an important role as a third line of defense in detecting, locating, and tracking the path of a storm. Reconnaissance aircraft, the second line of defense, provide direct, in-place measurements of the storm. By providing wind field data as well as other parameters essential to predicting the hurricane path, storm intensity is obtained. Weather satellites are the first line of defense by detecting the existence of the hurricane over the ocean expanse. Also, intensity can be inferred from the satellite images.

The role of radar in hurricane detection is limited by a nominal range of 125 to 200 miles. If we assume an effective 125-mile range for a Doppler radar, the wind field data for the storm should be continuously available within that range. Unfortunately, the radar cannot be expected to provide the 24-hour warning required for effective evacuation unless the hurricane is within radar range 24 hours before landfall. Some hurricanes do stall off the coast, e.g. Allen in 1980. In any case, a Doppler radar can provide the hurricane forecaster with invaluable information on the windfield for fine tuning of the location of the landfall and the storm intensity expected. The Doppler-derived wind data can be used to enhance the accuracy and the intensity of the storm surge forecast, thus providing an improvement over today's forecast. Similarly, radar wind field observations can be used to predict the very destructive storm surges accompanying slow moving extratropical storms.

Hurricanes spawn tornadoes. An average of nine tornadoes per hurricane (A.F. Sadowski 1966, Pearson and Sadowski 1965) tend to occur approximately 6 to 12 hours prior to the arrival of the hurricane-force winds. Typically, the path length and width of a hurricane-induced tornado is about half that of a non-hurricane tornado. Case Study CS-15 in Appendix C describes some tornado events associated with Hurricane Allen. Refer to the earlier discussion for the assessment of NEXRAD concerning tornadoes.

Very heavy rains may be associated with hurricanes. Hurricane intensity in terms of winds or minimum pressure is no indication of expected rainfall. The amount and intensity of rain at a particular location depends in part on the speed of the hurricane. The role of radar (Doppler and non-Doppler) in assessing the flood potential is discussed earlier.

NEXRAD Performance--The planned role for today's weather radar system in detecting, locating, and tracking hurricanes is well defined. (National Hurricane Operations Plan, FCM 77-2 NOAA). Unfortunately, the effectiveness of the weather radar system in contributing to its planned role in hurricane detection is not defined or assessed. Individual case studies of storms (NWS

Southern Region 1980) do describe and evaluate the role of weather radar. In Appendix C, Case Study CS-7 partially credits local weather radar observations with fine tuning of the Hurricane Agnes land fall.

The role of a NEXRAD radar in improving flood warnings is described earlier. The potential improvement of the NEXRAD radar over today's system is shown in Figure 14.

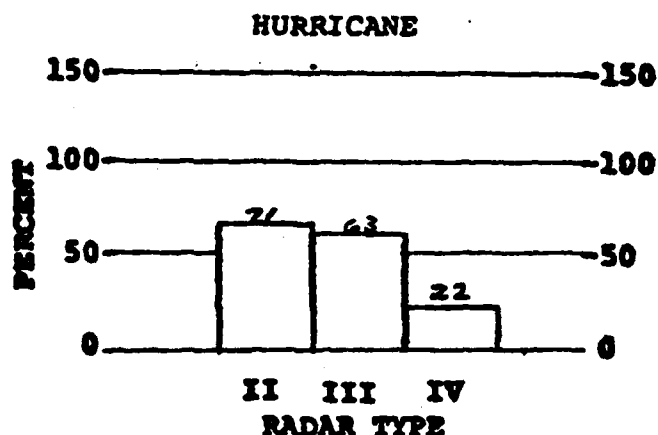


Figure 14.--Average percent improvement of radar type over WSR-57 from 14 responses (all data included).

Further comments of NEXRAD performance concerning hurricanes are contained in Appendix D.

As Doppler weather radars have not been deployed operationally in providing hurricane warning service, real time and actual experience in assessing the value of unique Doppler-derived wind data is not at hand. However, H. W. Baynton (1979) in the article, "The Case for Doppler Radars Along Our Hurricane Affected Coasts", and J. Wilson (et al. October 1980) describe the potential of Doppler radar to continuously monitor hurricane winds when the hurricane is within radar range (125 miles). The availability of the hurricane's wind field information on a continuous basis promises significant improvement in prediction of the wind hazard and storm surge. Both the NEXRAD non-Doppler and Doppler radars have the potential of improving the accuracy of locating the eye, or center of the hurricane.

Potential Benefits--Decisions on whether to flee or not to flee or to protect or not to protect property depends, among other factors, on weather information regarding the hurricane--its present and future path, the intensity and expected direction of the winds, the severity of the rainfall and the rate of movement of the storm.

The more credible and accurate predictions are, the greater the reduction in losses and costs of protection.

Three studies on hurricane warnings estimate their overall effects. Demsetz (1962) studied hurricane wind and flood damage (not storm surge) to Miami and concluded that the difference between perfect warning and no warning could be as much as 40 percent.

The hurricane warning system has been estimated by Sugg (1967) to save approximately \$25 million during the average season, and as much as \$100 million during a very active season, taking into account both the cost of overwarning and the fact that only a fraction of the population will take protective measures. Anderson and Burnham (1973) estimated the potential savings from a 50-percent improvement in forecasting using a combined game- and decision-theory approach, and concluded that resulting savings could be at least \$15 million in the first year.

W. A. R. Brinkman (1975) provides an excellent and broad survey of the hurricane hazard, the effects of the hazard, and the population and property at risk, including future estimates of population density along coastal areas. His chapter on Future Disaster: Miami, is reproduced as CS-16 in Appendix C.

Anderson and Burnham (1973) conclude that after 4 years of a reduced forecast error of 50 percent in hurricane landfall prediction, the benefits in reduced damage and cost avoidance for the U.S. Gulf of Mexico coastline will approach 195 million dollars (1973 paper) during the first 4-year period. Reduction in loss of life is not addressed in their analysis.

The simulations described by Baynton (1979) and the benefits to be derived from reduced forecast error using unique Doppler radar information indicate an appreciable contribution by NEXRAD in preventing hurricane losses. Because documentation of real world experience or other credible evidence does not exist, an estimate of potential benefits is considered a reasonable guess. Conservatively, we estimate a reduction in property loss of up to 10 percent and a reduction in a loss of life from 25 to 30 percent.

ANNUAL COSTS

<u>Deaths</u>	<u>Injuries</u>	<u>Property</u>	<u>TOTAL</u>
\$35.5M	\$ N/A	\$600M	\$635.5M

ANNUAL BENEFITS

\$8.7 to 10.9M	N/A	\$53 to 60M	\$61.7 to 70.9M
TOTAL POTENTIAL SAVINGS			\$61.7 to 79.9M

Windstorms

Costs--In addition to the wind hazards associated with hurricanes, tornadoes, and thunderstorms, severe wind storms are also related to certain weather patterns along the lee slopes of mountain ranges and extratropical cyclones--the large scale weather systems that move across the central United States bringing the familiar pattern of periods of stormy weather.

In an average year, the United States is threatened by more than 1,000 severe local wind storms and perhaps a dozen east coast winter storms. Although most cause little damage, approximately 33 storms annually are responsible for losses exceeding \$500,000, and several each year cause damages in excess of \$5 million. According to White and Haas, the largest single disaster was the Pacific Coast storm of October 11 through 13, 1962, which caused approximately \$250 million in damages in the coastal areas of California, Oregon, and Washington. Insured losses from wind storms have run between \$13 and \$16 million annually from 1942 to 1972.

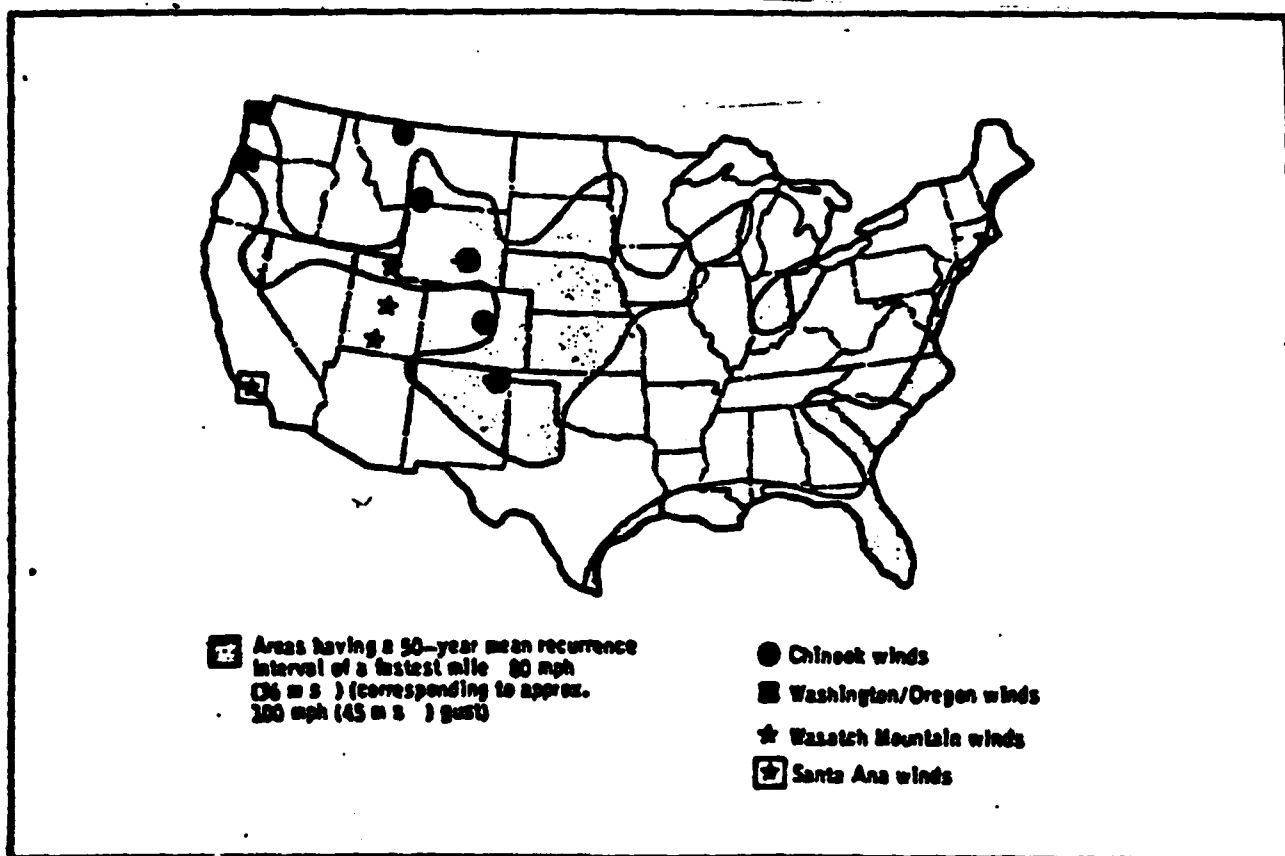
Benefits--The wind hazards associated with tornadoes, hurricanes, and thunderstorms including downbursts, gust fronts, and microbursts have been discussed already. Hazardous winds associated with extratropical cyclones, frontal surfaces, and downslope windstorms are considered here together with the ability to measure non-hazardous winds above the surface with Doppler radar.

Figure 15, taken from White and Haas (1975), shows the areas impacted by windstorms that cause widespread damage.

In Appendix C, Case Study C-17 dramatically describes the effects of a windstorm on the Hood Canal, Washington bridge on February 13, 1979 (Reed 1980). The need to reconstruct the likely wind behavior from available sources and the extreme winds (sustained winds of 70 knots and gusts close to 100 knots) being associated with a mesocyclone downwind of the Olympic peninsula mountains posed the question of the potential of a Doppler radar for furnishing the windfield data for some future similar occurrence.

Present day (non-Doppler) radars do not have the capability to measure the wind, although some wind data can be inferred by tracking echoes at a constant level.

Wind data can be a significant factor in applications other than those involving natural hazardous conditions. Presently, the weather forecaster uses the wind data available from rawinsonde stations with a 12-hour update cycle. In many instances, a clue to the generation of a new storm or to the rapid development of an existing storm can be obtained from changes in the wind field, especially if the changes are measured more frequently than 12 hours and describe the spatial relationships.



(adapted from Thom, 1968)

Figure 15.--Windstorm hazard areas.

Wind data are important factors for applications in air pollution and in determining emergency plans and evacuation routes in case of a serious nuclear accident. New Federal regulations require that nuclear plant operators maintain the ability to notify in 15 minutes everyone within 10 miles of a reactor in case of a serious nuclear accident. The new Nuclear Regulatory commission rules are an outgrowth of the incident at the Three Mile Island reactor in Pennsylvania in March 1979. These rules apply to all 73 operating reactors in the nation (Wald 1980). See Figure 16.

Sharp wind shifts associated with frontal boundaries may require realignment of the air traffic patterns into an airport with an attendant delay to the flow of aircraft in the air traffic control system.

NEXRAD Performance--The improvement in performance of the Doppler NEXRAD radars over the non-Doppler NEXRAD and today's system in measuring wind is especially noteworthy. Although the effectiveness of techniques for measuring clear air returns with a 10 cm Doppler

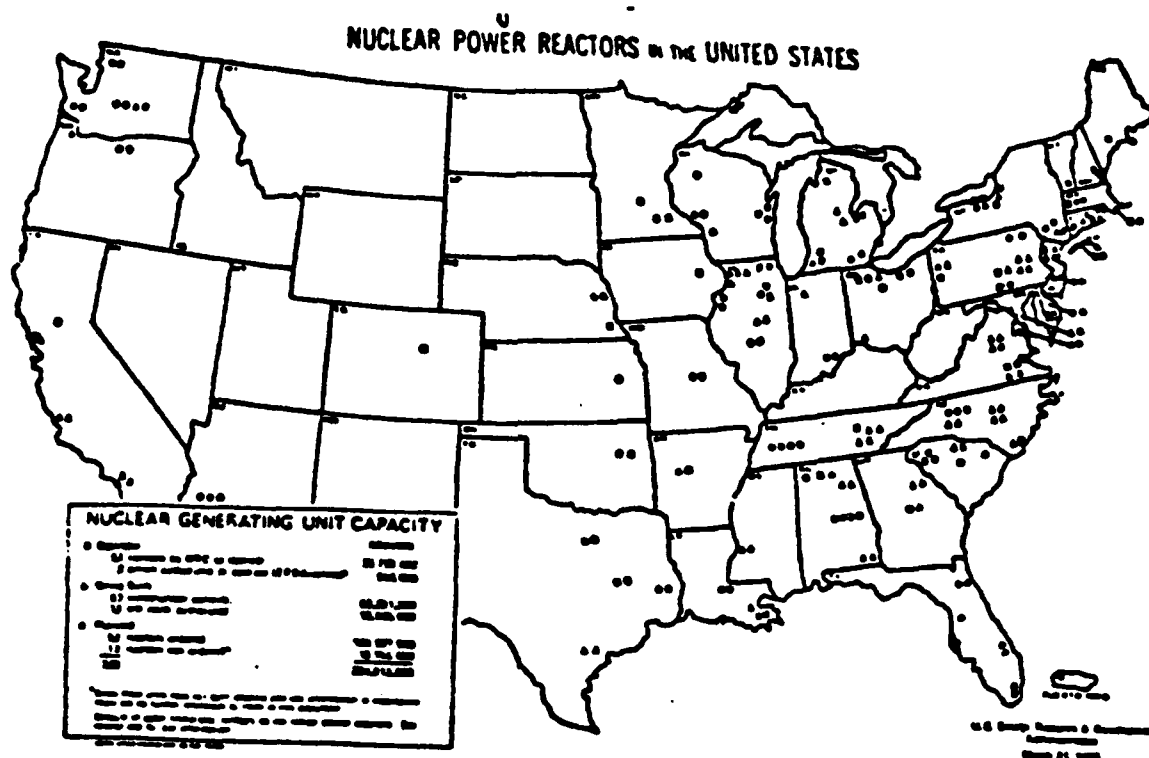


Figure 16.--Nuclear power plants in the United States currently operating, being built, or planned (after Abbey, 1975).

radar has not been established, the ability to measure wind when suitable patterns are present provides performance improvement for application in many fields of meteorology. Figure 17 indicates the weather radar experts estimate of the improvement of the Doppler Type II and Type III radars over the non-Doppler Type IV. Individual comments are contained in Appendix D for this phenomenon.

At present, data on such factors as an update rate to optimize the NEXRAD capability in the event of a Chinook-type wind threat, or an optimal update rate for the onset of Santa Ana-type winds are not available. An update rate of less than 6 minutes may be optimal for these phenomenon while the 6 to 12-minute update rate may be adequate for detection and warning of winds associated with frontal movement and other similar larger scale phenomena. Recognition of

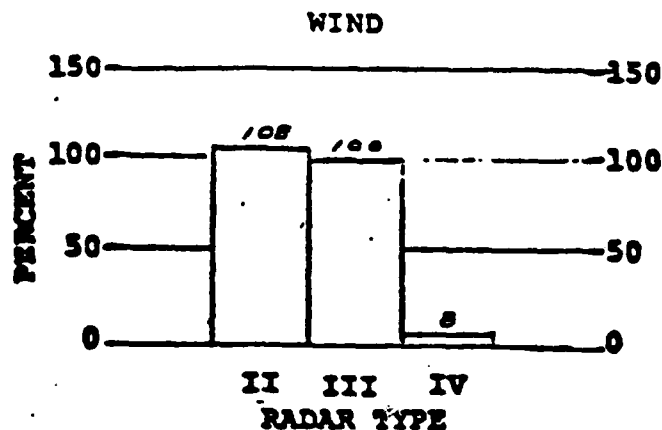


Figure 17.--Average percent improvement of radar type over WSR-57 from 14 responses (All Data Included).

such factors led to a suggestion that the radar scanning procedure adopted should be a function of the phenomenon being observed and thus avoid the restriction to the system operation of a single scanning procedure for all meteorological conditions.

Potential Benefits--All of the potential benefits to be reaped from the improved performance of NEXRAD radars in providing the basis for a wind warning, or in providing almost continuously available wind field data in storms, to the weather service system are not quantifiable in terms of dollar values as of this writing. This is in part due to the lack of information on those wind losses, other than those due to thunderstorm, tornadoes, and hurricanes, that are preventable losses and to a lack of information on the demonstrated capability of the weather service system to use Doppler radar derived winds in real time.

However, the potential benefit of having almost continuous wind field data available is tremendous in being able to detect, locate, and quantify this parameter.

Wind in general is extremely variable in time and space. The disturbances responsible for damaging winds are relatively short-lived and of small areal extent, except for frontal systems. Synoptic reporting weather stations are approximately 100 miles apart for surface observations and 300 miles for upper air observations. Consequently, the size of observable disturbances measured without radar is on the order of several hundred miles. Local weather forecasts are improved if information on a small scale, such as that obtained from radar, is available.

Micro- and meso-scale systems are predicted through extrapolation from synoptic patterns, and little prediction capability is claimed. Major problems are mathematical and theoretical difficulties in developing predictive models for small scale disturbances, the necessary accuracy and number of observations, and the short time available for processing, interpretation, and dissemination of results (National Research Council 1971).

Thunderstorms and squall lines are difficult to forecast prior to formation. The benefit to be gained from the capability to measure winds in "optically clear air" is significant as it derives from improving the forecasting of the initiation of convection and from an increase in the understanding and subsequent forecast accuracy of those small scale phenomena presently undetected by the observation networks.

Some examples of potential applications from this unique Doppler capability are:

- Low level wind shear hazard to aircraft--especially the wind shears that occur in other than thunderstorms conditions
- Development of an East Coast "Northeaster" off of Hatteras, North Carolina--the availability of wind data on a nominal 15-minute update rather than a 720-minute update available on an area basis rather than from a point source leading to an improvement in existence, timing, and intensity determinations of East Coast winterstorms
- Aid in determining evacuation routes for emergency conditions in the vicinity of a nuclear reactor--continuously available windfield information to aid in determining whether to evacuate or not and what evacuation routes are best
- Prediction of the time of onset and of the wind field direction and intensity of frontal-type windfield changes to more effectively manage the aircraft flow to and from major airports

To obtain these types of gains in weather service to the public and other users, an aggressive technique development program should provide operating procedures by the NEXRAD implementation date of the late 1980's. An estimated annual benefit of more than \$2 million will accrue through reduction of costs of delay to air carriers and passengers. See the discussion of Costs and Benefits Related to Specific Users: Civil Aviation and Military. Benefits have not been assessed for emergency evacuation decisions in the vicinity of nuclear plants. Further analysis of this NEXRAD capability is suggested.

The following listing summarizes information concerning costs and potential savings for windstorms.

ANNUAL COSTS

<u>Deaths</u>	<u>Injuries</u>	<u>Property and Other</u>	<u>TOTAL</u>
\$54.6M	N/A	\$549.6M	\$604.2M

ANNUAL BENEFITS

\$N/T	N/A	\$ 2.5M	\$ 2.5M
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TOTAL POTENTIAL SAVINGS			\$ 2.5M
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N/T--Not Taken

Severe Winter Storms

Costs--White and Haas state that urban snow and wind storms cause as many deaths as tornadoes. The fatal coronary arrest in the midst of snow shoveling equals the violent deaths from tornado debris. Tornado deaths typically command more public attention while the scattered and less dramatic losses through urban snow attract little attention.

In terms of property losses, those due to the urban storm or severe winter storms range between \$10 and \$20 million annually. However, the other costs related to severe winter storms in terms of snow removal and disruption of services, including industrial production and other commercial enterprises, are not readily available. In one instance the NOAA Environmental Data Information Service estimated that the total economic loss to the Buffalo, N.Y. area from the January 1977 blizzard due to storm damage, snow removal costs, lost wages, and lost production was \$250 million.

If we look at the impact of snow and ice on one of the users of weather information, we find that in the case of air transportation, snow and ice are responsible for over 23 percent of the weather-related air traffic delays of 30 minutes or longer. Based on information provided by the Air Transport Association (ATA) and the FAA, these delays equate to an annual cost of approximately \$190 million.

The unexpected occurrence of a relatively large amount of snow in a very short period of time overwhelms urban snow-removal operations and curtails movement. A false alarm of heavy snow may lead city officials to costly mobilization activities. When that happens often enough the forecasts tend to be ignored.

Mileti (1975) states that in addition to the difficulties in disseminating weather forecasts and the ability of persons who

receive warnings to interpret them, the accuracy of snow predictions are constraints inhibiting the effectiveness of snow emergency procedures. One of the particularly difficult tasks in snow forecasts is the extreme precision required regarding moisture content, as well as the rapid and erratic movement of the storm systems. More accurate information must be based on shorter warning periods.

Information on deaths and property losses directly attributable to snow and ice are very difficult to obtain. However, the Insurance Service Office (1980) reports a catastrophe in California in 1978 in which \$4.6 million in property damage was a result of wind, snow, and ice. Again in 1978 the Insurance Service Office relates wind, snow, and ice damage over \$1.7 billion caused by storms in the northeast United States. In addition, the Hammond Almanac (1980) lists a blizzard that took place March 22 to 25, 1957, in the Midwest that claimed 21 lives and caused property damage between \$5 and \$6 million. Bussel (et al. 1978) of the United Kingdom predicts a savings of 200,000 pounds sterling per year with more accurate short term forecasts of snow based on an improved radar storm detection system.

Benefits--Severe winter storms have an impact on a widespread area and are usually well defined and analyzed using conventional synoptic scale methods. Prediction of the 12- to 24-hour location and intensity is also handled with present day prediction methods. The role of weather radar and particularly the NEXRAD type radar in forecasting winter storms is the potential contribution of a continuously available wind field in the suspected area of storm formation.

Determination of the onset of snow, its intensity, and duration as well as defining the "bright line" and predicting the depth of the snow are significant inputs to decisions regarding handling the preparations for snow removal, rescheduling of school and work hours, etc. Today's radar systems do help in detecting the areal and vertical extent of precipitation.

NEXRAD Performance--Today's weather radar system provides input into the onset of a winter storm by "fine tuning" the data for local forecasts. The NEXRAD Doppler radars could be used to locate and provide useful data on the time of arrival and the intensity of the lines of wind shift accompanying fronts of winter cyclones. Additional comments on the performance of the radar with regard to storms appear later in this report.

Figure 18 indicates the estimate of improvement of NEXRAD radars over today's WSR-57.

Potential Benefits--The potential benefits from operation of NEXRAD in the forecasting of severe winter storms are difficult to quantify at this time. The value to the forecaster of Doppler radar derived wind field information has been discussed earlier. The value of the

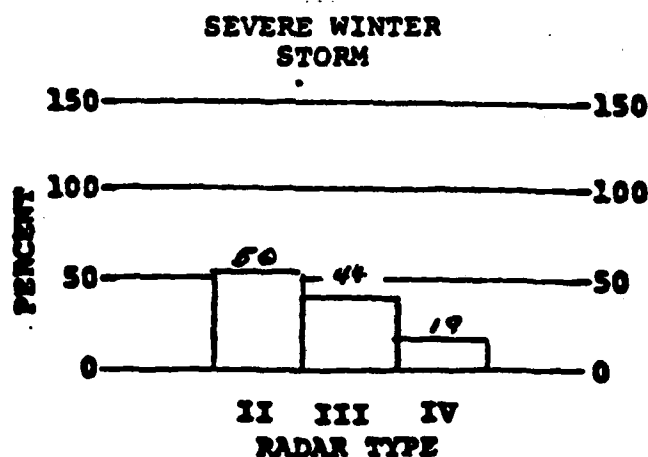
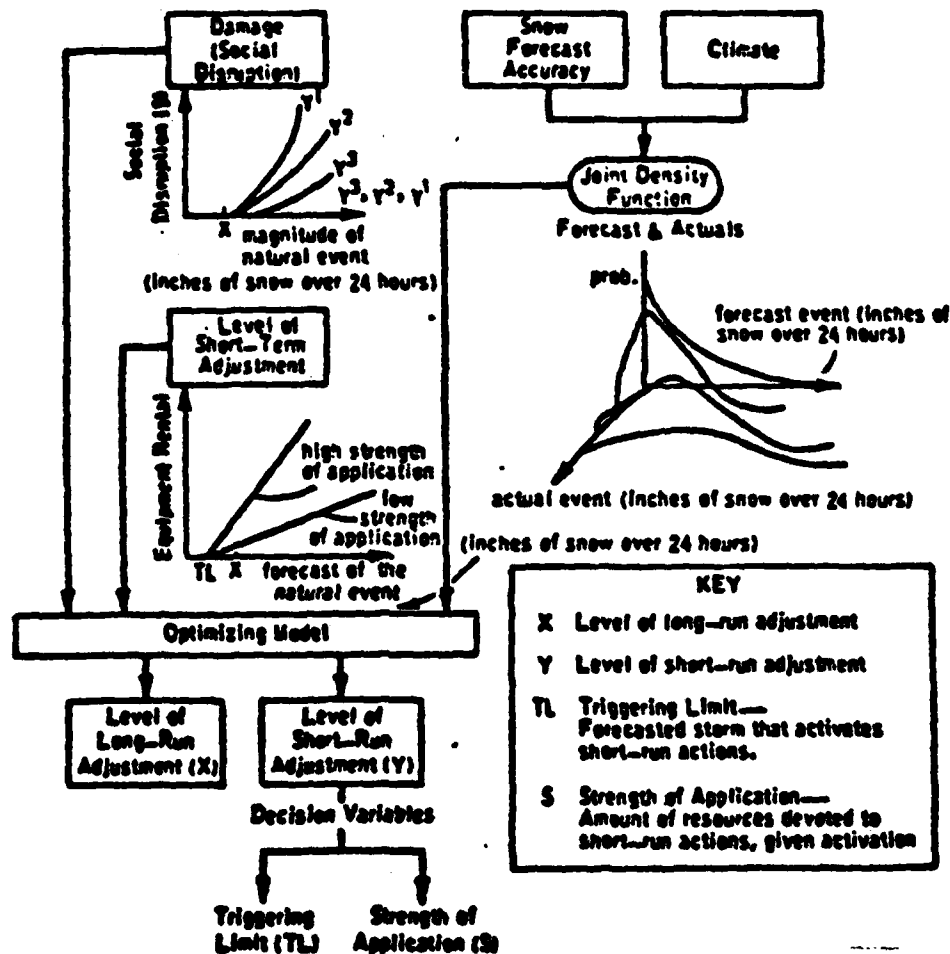


Figure 18.--Average percent improvement of radar type over WSR-57 from 14 responses (All Data Included).

contribution of such data to the improvement in the accuracy of the winter storm forecast lies in the extent that such data will provide, for example, the early and yet credible clues that a "Northeaster" is fermenting off Cape Hatteras and will become the dominant cyclone influencing the East Coast in the subsequent 2 or 3 days.

Benefits and savings through improved forecasts can affect not only the urban areas affected by the storm but information can be provided on decisions to minimize the affect on air commerce and other forms of transportation. White and Haas (1975) have modeled the urban snow decision process (Figure 19). Cooley and Denouin (1972) indicate gradual improvement in the accuracy of National Weather Service forecasts. However, they note, that for the nation in 1971 and 1972, in terms of 12-hour warnings of 4 inches or more of snow, only approximately 30 percent of the area, in square degrees of latitude, for which snow was predicted actually received the forecast amount. City officials can usually obtain more accurate information on shorter warning periods from multiple information sources (Bauman and Russell 1971, Foster 1970).

Suchman (et al. 1979) in their comprehensive analysis of the impact of weather forecasts of timing and of the amount, within specified limits, of snow and ice, provide an insight into the economic advantages and losses incurred by local governments of various populations and geographic locations. The mean annual ice/snow budget of a local government ranges from a maximum of \$853,000 to a minimum of \$10,000 dependent on many factors.



AFTER WHITE AND
HAAS, 1975

Figure 19.--Model in symbolic form (urban snow)

We estimate that NEXRAD with Doppler capability will improve the 12-hour forecast of the development and movement of winter storms as well as provide locally available accurate information with regards to the onset of snow/ice. Benefits accrue in reducing costs of snow removal by reducing alert and standby time (Appendix C-11) permitting effective scheduling of school closings, delivery of goods,

air transportation, and reducing impact of electrical power outages. Benefits of \$19 million through reduction of delay due to severe winter storms is estimated for the air carrier industry, including passengers. See the discussion of Costs and Benefits Related to Specific Users: Civil Aviation and Military. Additional benefits to the nation for improved forecasts of the onset of snow/ice storms are not quantified but are considered significant.

The following listing summarizes information concerning costs and potential savings for severe winter storms.

ANNUAL COSTS

<u>Deaths</u>	<u>Injuries</u>	<u>Property and Other</u>	<u>TOTAL</u>
\$28.9M	\$2.5M	\$690M	\$721.4M

ANNUAL BENEFITS

N/T	N/T	\$19.0M	\$19.0M
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TOTAL POTENTIAL SAVINGS	\$19.0M
--------------------------------	----------------

*Only Air Carrier and Passenger Delay Reduction Costs

Turbulence

Costs--The National Transportation Safety Board (NTSB) maintains a data base on turbulence-related incidents. Tables 25 and 26 indicate the annual number of incidents that the Board investigated of turbulence in clouds and thunderstorms and of turbulence in clear Air for the years 1975 through 1979. In another somewhat earlier study relating to causes of air carrier accidents (Connor and Hamilton 1980), costs in 1974 dollars for clouds and thunderstorm-related turbulence are estimated to be \$23,275,000 and for clear air turbulence as \$5,512,000. This same study also investigated general aviation accidents but did not provide separate costs estimates for turbulence in a similar fashion.

Table 25.--Accidents/incidents involving turbulence in flight (in clouds/thunderstorms) as cause/factor--U.S. Civil Aviation 1975 to 1979 (NTSB investigated incidents only)

Year	Total*	Injury Index			
		Fatal*	Serious*	Minor*	None
1975	40	23	6	4	7
1976	33	19	9	1	4
1977	37	16	8	4	9
1978	31	21	6	2	2
1979	28	20	4	0	4
Total	169	99	33	11	26
Avg.	33.8	19.8	6.6	2.2	5.2

*Number of Incidents

Benefits--Turbulence associated with thunderstorms as well as that which occurs from other causes is discussed here. Turbulence, whether arising from convective processes or mechanical overturning, can affect aircraft operations. Table 27 provides some indication of the dimensions of the types of turbulence affecting aircraft operation (Bromley 1972).

In today's aviation system, weather radar, airborne or ground based, is the prime sensor used to provide information on turbulence associated with thunderstorms. The radar does an excellent job of providing a measurement of reflectivity and this indicator of storm intensity is indicative of turbulence that might be expected somewhere in the storm system. However, the correlation between turbulence and radar reflectivity along the flight path is small (Lee and Carpenter 1979). In recognition of this, the FAA's Advisory Circular on Severe Weather Avoidance (FAA 1976) states: "It must be recognized that those weather echoes observed on radar (airborne or ground) are a direct result of precipitation. RADAR DOES NOT DISPLAY TURBULENCE. It is acknowledged that turbulence is generally associated with heavy areas of precipitation; however, the radars used for air traffic control purposes are not capable of equally displaying precipitation information. Under certain conditions, in the past, echoes received from precipitation rendered ATC radar unusable. To avoid such disruption to radar service, modifications designed to considerably reduce precipitation clutter were added to ATC radar systems. This feature, known as Circular Polarization (CP), eliminates all but the heaviest areas of precipitation. terminal radar systems use this feature as necessary to reduce precipitation clutter during moderate to heavy rain or snow. Moderate to heavy precipitation areas appear on the radar scope as white areas--something like "snow" on your TV, only brighter."

Table 26.--Accidents/incidents involving clear air turbulence as cause/factor--U.S. Civil Aviation 1975 to 1979
(NTSB investigated incidents only)

Year	Total*	Injury Index			
		Fatal*	Serious*	Minor*	None
1975	18	2	9	3	4
1976	17	3	2	2	10
1977	14	5	6	2	1
1978	11	3	4	1	3
1979	5	1	0	1	3
Total	65	14*	21	9	21
Avg.	13	2.8	4.2	1.8	4.2

*Number of incidents

Table 27.--Dimensions of turbulence

	Horizontal	Vertical	Time
Clear Air Turbulence	Tens of Miles	Few Thousand Feet	Tens of Minutes to Few Hours
Wake Turbulence	Hundreds of Feet	Hundreds of Feet	A Few to Ten Minutes
Severe Storm Turbulence	Hundreds of Miles	Thousands of Feet	Several Minutes To Several Hours

However, with full realization of these limitations on detecting turbulence with today's radar, the Australian Department of Transport recognizes the importance of a turbulence advisory service for safe and effective movement of air commerce. The Terminal Area Severe Turbulence Service (TAST) as practiced at three major Australian Airports, combines the present weather radar sensing capability with a meteorologist on site to provide the air traffic controllers with reports of severe convective turbulence associated with thunderstorms occurring within 60 miles of their airport. This information is provided to the pilot as advice on hazardous weather and to the controller for his assessment in modifying clearance, providing diversions, or temporarily closing the appropriate air-space or runway access.

Turbulence occurring in clear air is not seen on today's radars and other techniques are used to minimize the effect of this hazard.

NEXRAD Performance--The improvement in detecting, locating, and measuring turbulence associated with thunderstorms is appreciable if Doppler weather radar is used. The capability of a NEXRAD Doppler radar (10 cm) to measure the turbulence associated with clear air in a volume lacking suitable scatterers is less well defined. Recent work by R. Crane (1980) points out the existence of turbulence, undetected by a 10-cm radar, in the clear areas between thunderstorm cells. Further assessment of the impact of this type of turbulence on aviation operation is needed. Detection of clear air echoes with a 5-cm radar in non-winter situations is routine (Wilson et al. 1980). J. T. Lee (1977) reports on the potential of measuring the spectrum broadness of the radial velocity with Doppler radar and presenting such data on a multi-moment display which provides in real time the reflectivity, mean velocity, and spectrum broadness at grid locations within a storm. He concludes that the goal of increased safety and better utilization of air space in thunderstorm condition appears attainable. The estimated improvement in NEXRAD Doppler radar over non-Doppler radar is shown in Figure 20.

Additional comments of the weather radar experts on NEXRAD performance are found in Appendix D.

Potential Benefits--Potential benefits from improvement in NEXRAD performance in detecting, locating, and measuring turbulence associated with thunderstorms in terms of safety and efficiency are anticipated. Benefits from measurement of clear air turbulence or turbulence associated with wake vortices can be assessed when results of ongoing research efforts are evaluated.

The study "Evaluation of Safety Programs with Respect to the Causes of Air Traffic Accidents" (T. M. Connor and C. W. Hamilton 1980), suggests: "Hazardous weather increases the probability of an accident, especially in conjunction with other system failures, e.g. an engine failure in flight or pilot error/cognition. An apparent anomaly associated with this finding is that the safety programs

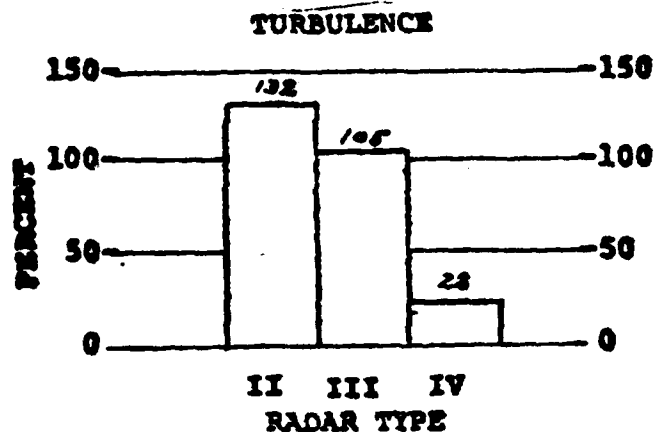


Figure 20.--Average percent improvement of radar type over WSR-57 from 13 responses (all data included)*.

aligned with this hazard are effective. The forecasting, analyzing, detection, and weather reporting components are available on demand for air carriers. The regulations and procedures, both Government and air carrier, that have been established for operating in this weather environment are based on experience and are designed to permit the maximum level of safe weather operations. The resolution of this anomaly lies in the cause/factor combination, pilot error and weather. The cause/effect relationship between these cause/factors and its associations with system tolerances do not appear to be well-understood.

The major areas for improvement in this category of programs include the means for more timely communications and use of pertinent weather data and review of external pressures and procedures influencing pilot behavior under weather-related critical conditions".

The benefits from the use of NEXRAD Doppler radar to measure turbulence in terminal area operation are not readily translated into dollar values. Improvement through actual measurement of intense turbulent areas rather than deriving the location, and intensity by inference from reflectivity signatures should provide the ground based weather and air traffic control systems information that will enhance safety as well as allow more efficient use of airspace--especially in the terminal area environment. The ways and means of providing this NEXRAD derived information to the airborne pilot is currently under study.

Icing

Costs--Icing as considered in this section is that phenomenon that affects aircraft in flight. Ice storms and icing on the ground are considered to be included as phenomena associated with severe winter storms.

The NTSB information storage data base on aircraft accidents/incidents involving icing for the years 1975 through 1979 are shown in Table 28. Dollar values of losses due to this phenomenon are not identified in this data base and are not readily derived in any known references.

Table 28.--Accidents/incidents involving icing conditions as cause/factor--U.S. civil aviation 1975 to 1979
(NTSB investigated incidents only)

Year	Total*	Injury Index			
		Fatal*	Serious*	Minor*	None
1975	53	28	6	4	15
1976	44	18	9	5	12
1977	36	20	5	5	6
1978	57	38	5	3	11
1979	50	33	5	5	7
Total	240	137	30	22	51
Avg.	48	27.4	6.0	4.4	10.2

*Number of Incidents

Source: NTSB

Benefits--The role of weather radar in detecting, locating, and measuring the intensity of icing conditions in the atmosphere is a secondary one, at best. The appearance of the bright band, the enhanced reflectivity from wet snow, melting as it falls through the 0°C isotherm in a radar return, can indicate the level of the 0°C isotherm. Icing conditions that may occur in convective showers and thunderstorms are more readily inferred using radar.

Icing is of particular concern in helicopter operation. Although icing in convective showers can be inferred, icing that occurs in the stratiform clouds is not discernible as the water droplets are too small to be detected by the radar.

NEXRAD Performance--Improvement in detecting and measuring icing situations with today's system will be relatively small. Any improvement will come from the increased sensitivity and spatial resolution inherent in both the proposed Doppler and non-Doppler NEXRAD and any enhancements in "bright band" depiction (C. G. Collier et al. 1980). Figure 21 indicates the percentage of improvement in performance of the NEXRAD over today's weather radar.

Potential Benefits--Benefits to accrue from NEXRAD improvement in the measurement of icing cannot be quantitatively assessed at this time. The contribution of NEXRAD weather radar in supporting helicopter operations by detecting, locating, and measuring icing situations, particularly in overwater operations, has yet to be assessed. However, when these radar observations are integrated with other information from the observing networks, including cloud observations from satellites, a significant benefit to helicopter operations is quite probable.

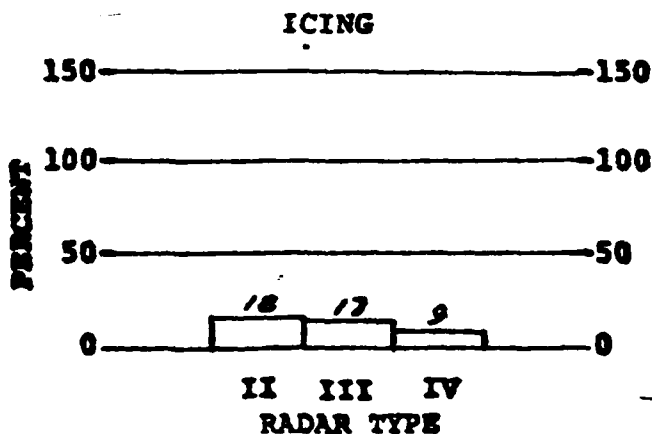


Figure 21.--Average percent improvement of radar type over WSR-57 from 14 responses (all data included).

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PRELIMINARY COST BENEFIT ASSESSMENT OF SYSTEMS FOR
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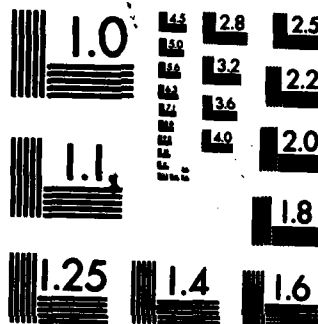
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Hail

Costs--Hail damage rarely causes human death or injury, but hail damage to crops and property is estimated at more than \$750 million. According to White and Haas, hail damage reverses the pattern of tornado damage; that is, rarely are any human deaths or injuries caused by hail, but its economic impact is severe. Approximately 2 percent of the national crop production is lost annually through the hail hazard. The annual crop loss to hail in the United States is estimated at \$685 million and the annual property loss may be approximately \$75 million; the net economic impact on the nation is large.

Benefits--Hailstones are precipitation in the form of lumps of ice that occur during some thunderstorms. Hailstones range from pea size to the size of a grapefruit. They are usually round but may also be irregular in shape, some with pointed projections.

The detection and recognition of hail by weather radar is associated with high reflectivity values. Most of the hail indicators (Hamilton 1969) are empirically determined and show modest success but with high false alarm rates (Foster 1976, Burgess et al. 1978). L. R. Lemon (1978) suggests that the WSR-57 criteria for severe hailstorm identification as derived from his study are: peak mid-level (5 to 12 km AGL) reflectivities must be 45 dBZ; mid-level echo overhang must extend at least 6 km beyond the outer edge of (or beyond the strongest reflectivity gradient of) the low-level (1.5 km AGL) echo; and the highest echo top must be located on the storm flank that possesses the overhang and lie above the low-level reflectivity gradient between the echo core and echo edge or lie above the overhang itself.

Hail damage to crops is significant. However, other than through modification techniques, little can be done to reduce this type of loss. However, with movable or protectable property, early notification of hail occurrence can be helpful (Appendix C, Case Study CS-10).

NEXRAD Performance

The improvement in detection of hail will derive from the improvement of time and spatial resolution of the NEXRAD over today's radar system. The addition of automated elevation sampling should provide more readily available analysis of the potential of hail. The use of Doppler does not offer any appreciable advantage except that Doppler radar identification of a mesocyclone circulation has increased the ability to identify severe thunderstorms with attendant hail. Some of the radar experts urge the use of dual-frequency and/or different polarizations to improve identification of hail occurrence.

Figure 22 together with the comments concerning hail in Appendix D indicate the performance improvement over today's system.

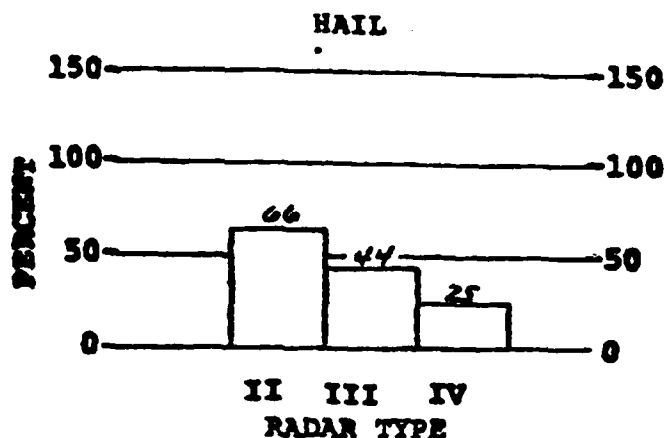


Figure 22.--Average percent improvement of radar type over WSR-57 from 14 responses (all data included).

Potential Benefits--The potential benefits to accrue from improved NEXRAD performance on hail detection have not been assessed in terms of dollar values. Although the losses due to hail damage are appreciable, the preventable loss creditable to improved radar performance in hail detection cannot readily be isolated from the capability of detecting severe thunderstorms. Most of the national losses reflect crop loss.

Individual case studies on the hangaring of aircraft prior to a hail occurrence show the potential benefits. It is anticipated that an improvement both in the timing and credibility of the onset of severe thunderstorms will provide benefits by preventing loss of movable property and in preventing loss of productivity due to false warnings of occurrence.

ANNUAL COSTS

<u>Deaths</u>	<u>Injuries</u>	<u>Property & Other</u>	<u>TOTAL</u>
N/A	N/A	\$850M	\$850M

ANNUAL BENEFITS

N/A	N/A	N/T	N/T
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TOTAL POTENTIAL SAVINGS	N/T
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Costs and Benefits Related to Specific Users: Civil Aviation and Military

Introduction

In the process of segregating costs and benefits to the three user groups: the general public, the military, and civil aviation, it became apparent that the data base on hazardous weather costs and losses primarily contained information dealing with the general public. Information on civil aviation is focused on the "cause/factor" in weather related accidents and losses due to operational delays. Analysis and evaluation of these data is described in this section.

The information on these costs to the military is not readily available from a structured data base comparable to that available from the general public sources.

Individual case studies are cited in Volume II, Appendix C, to provide illustrations of the impact of severe weather on the military. Most of these case studies have been made available by the USAF's Air Weather Service and thus reflect the impact of hazardous weather only on a portion of the military services. Our findings and conclusions are those that can be supported by the available data and information.

Civil Aviation

The air carrier industry attributes significant operational losses due to delay in making published schedules. These increased costs are in part due to the occurrence of severe and hazardous weather primarily in the terminal areas.

United Research Inc. (1961) estimated that annual weather losses due to cancellations, delays, and diversion of airline flights in the U.S. during the early 1960's would approximate \$55 million. Bollay Associates (1962) predicted that similar losses in 1970 would be \$148 million.

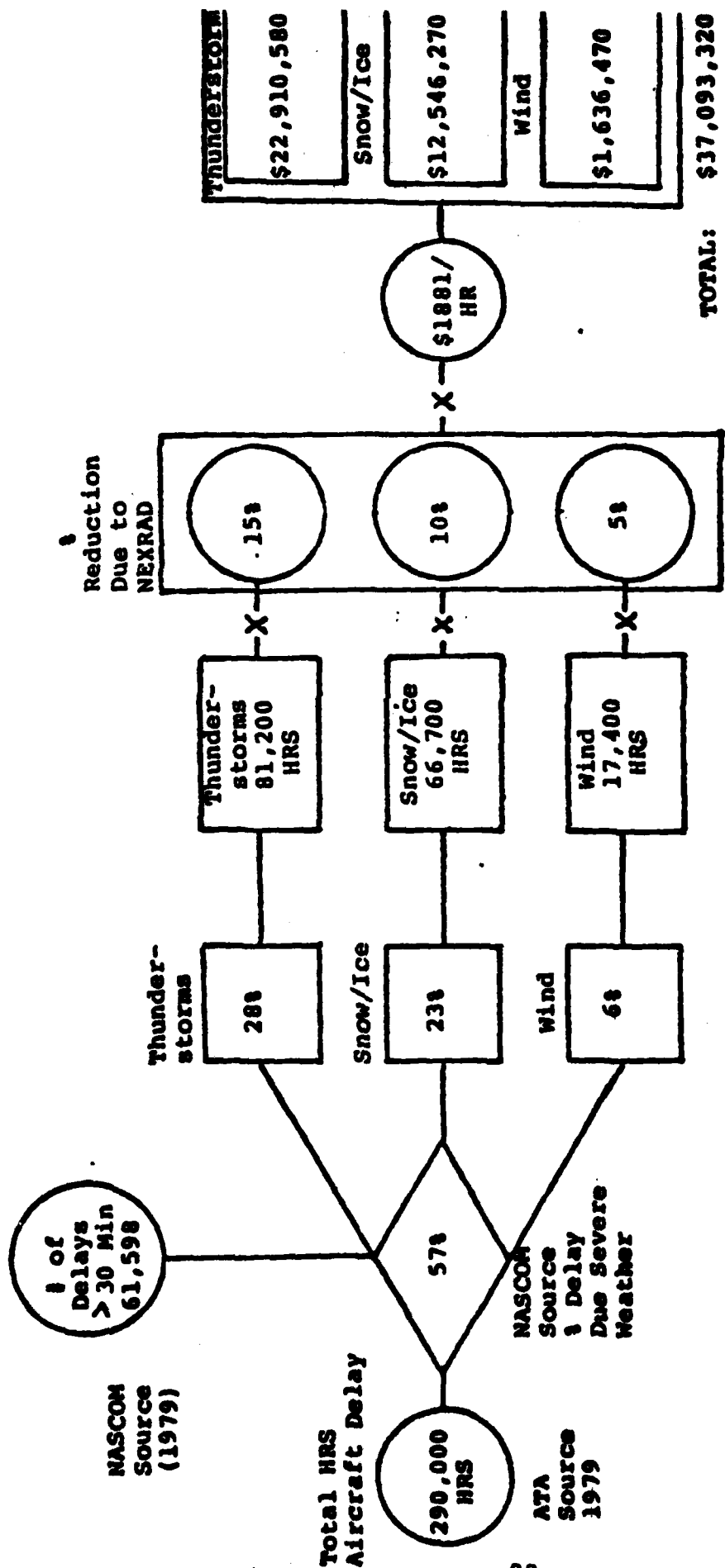
To assess the magnitude of the current costs, direct operating costs to air carriers, and of delay due to severe weather, an estimating procedure described in Figure 23A has been devised and applied to 1979 data. The uncertainty in this calculation stems from the assumption that the percentage of delays of 30 minutes or more (1979 FAA-NASCOM data) is representative of all delays. Figure 23B shows the estimated cost of delay due to severe weather, a figure compatible with Bollay's 1962 estimate for the 1970's. A similar estimating procedure for calculating costs to passengers due to severe weather indicates \$311 million losses by air carrier passenger due to hazardous weather. Values used to obtain this estimate are shown in Figure 24.

Benefit to Civil Aviation--Benefits can accrue to the air carrier industry and to the air carrier passenger by the reduction of operational delays and therefore the costs associated with such delays. The NEXRAD System can provide such a benefit by making severe weather information available for use by the terminal air traffic control specialists in managing the flow of traffic to and from a busy airport. Figure 25 depicts a method of estimating a reduction in delay due to improved weather radar information in the terminal area air traffic control operation. The estimates are based on assumptions of the percentage of reduction in delay that would result from use of a NEXRAD System.

Uncertainty in this estimate results from: the assumption that the percentage of delays of over 30 minutes as reported in NASCOM are representative of all delays, and the lack of precision in the estimate of delay reduction achievable as a result of NEXRAD deployment. Unfortunately, simulation of the delay reduction potential of an improved weather radar communications and observing system has not yet been accomplished.

Frankel (1980), in his benefit analysis of a proposed Aviation Weather System, provides an estimate of the maximum possible reduction in airborne delay and fuel consumption with the view that actual computation of the amount of weather-caused delay reduction is not currently feasible. His estimate, using 1977 data, is for a maximum possible reduction of 166,800 hours in airborne delay with maximum possible associated fuel savings of 248 million gallons of fuel. In the year 1990, Frankel estimates that these possible savings will grow to 205,800 hours and 306.8 million gallons of fuel.

Figure 26 shows an estimate of benefits in reducing the direct operating costs to air carrier aviation of dollars that is likely to result from the deployment of NEXRAD. This estimate has been accomplished using the methodology outlined in Figure 25 and claims savings equivalent to \$19 million per year. The dollar value of benefits to passengers estimated similarly equals \$37 million per year. See Figure 24 and Table 29.



* Value of Passenger Time - \$19/HR.
Average 99 Passenger/
Aircraft
= \$1,881/HR.

(1979 ATA Data)

Figure 24.--Benefit to aviation assessment--severe weather
(reduction in passenger delay costs*)

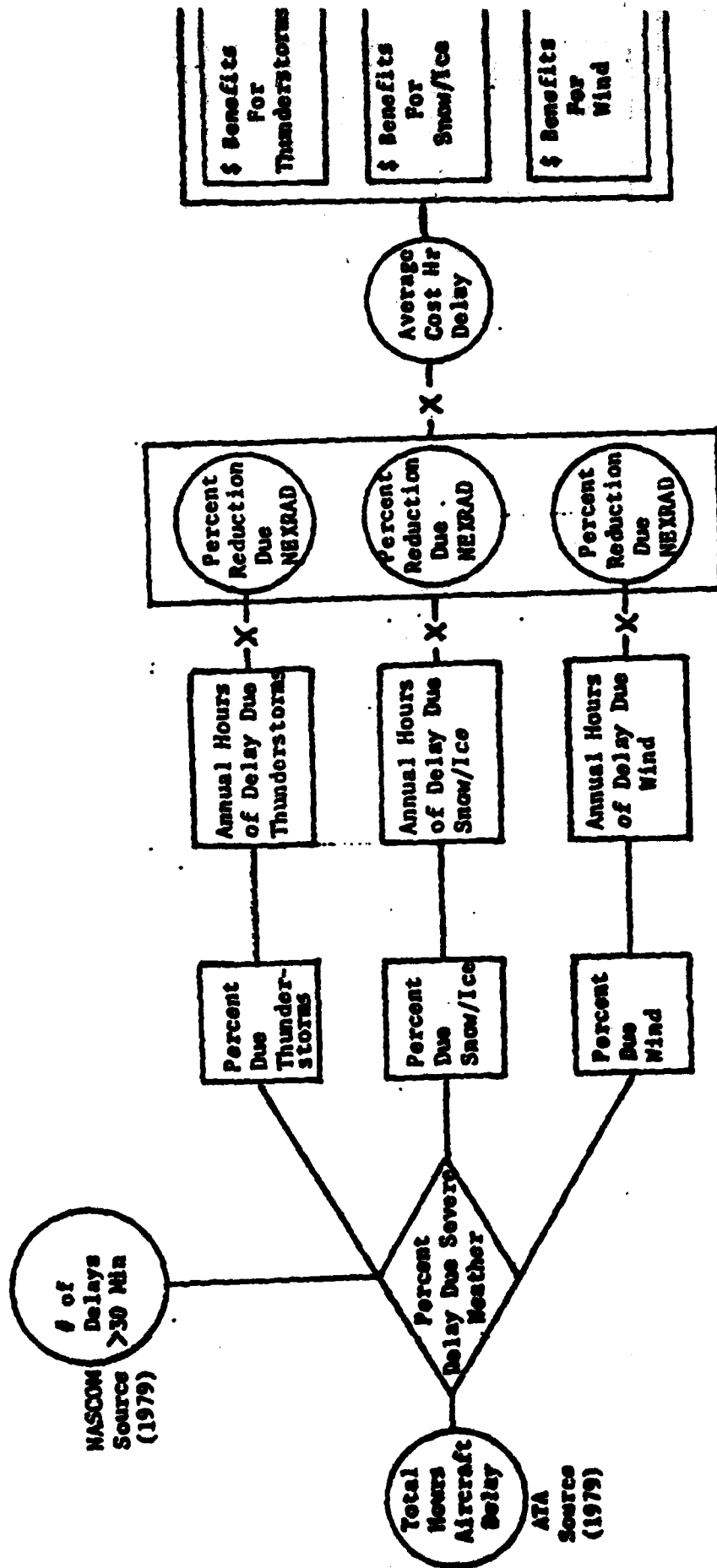


Figure 25.--Benefit to aviation assessment--severe weather.

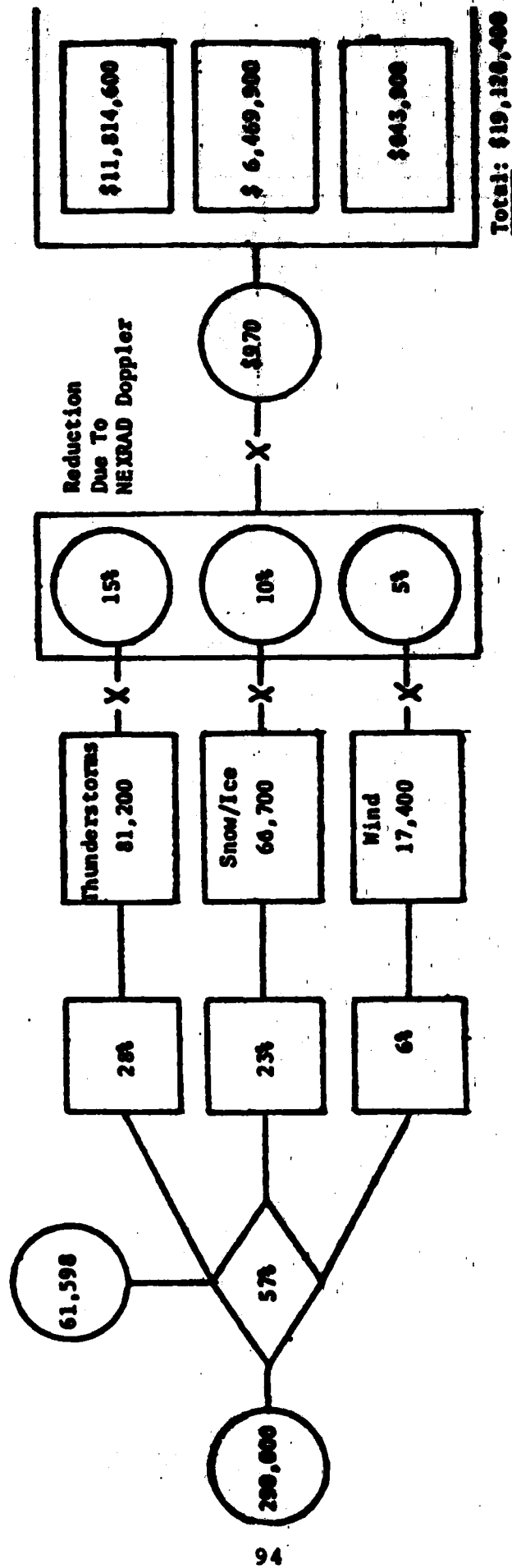


Figure 26.--Benefit to aviation assessment--severe weather
(reduction in operating costs)

Table 29.--Estimates of certain delay-related benefits to civil aviation (air carrier including passenger benefits) (\$ in millions)

	Direct Operating Costs	Reduction in Pass Delay	Total
Thunderstorms	11.8	22.9	34.7
Snow/Ice	6.5	12.5	19.0
Wind	.9	1.6	2.5
Total	19.2	37.0	56.2

Frankel (1980) estimates the potential annual dollar value of safety improvements to be between \$5.8 and \$19.5 million when improvements in the method of disseminating and detecting thunderstorms and related wind shears are implemented.

Military

This preliminary cost/benefit assessment draws heavily on the information, data, and analysis made available by the U.S. Air Force, especially AWS. The data base reflects case studies drawn from the AWS files for bases in the United States and does not include information from overseas. Costs and benefits from wartime application of weather radar are not included. Information on costs and benefits to the U.S. Navy and U.S. Army are not included. Thus, the limitations imposed by these data voids should be recognized in interpreting the findings and conclusions.

To provide a basis for estimating the losses due to hazardous weather at U.S. Air Force bases, an analysis of ground mishap data for 5 years, 1976 through 1980, is presented in Table 30. The cost figures are segregated into hazardous weather categories somewhat different from those used throughout the rest of this report. Additionally, only total costs rather than preventable and non-preventable categories of cost figures are available and are listed as a single figure in the table.

Benefits to Military--Benefits are estimated from U.S. Air Force data only. The benefits are calculated using different analysis methods than those used in the rest of the report. For example, the benefits of NEXRAD for tornadoes, hail, and strong winds associated with thunderstorms have been determined collectively by the U.S. Air Force's AWS.

We assume 200 military installations with resources protectable from severe thunderstorms and approximately 10 severe thunderstorm point warnings (PWS) issued each year for each installation. That totals 2,000 PWS. The verification of these warnings with and without Doppler radar is summarized as follows. (These tables were

Table 30.--Summary of ground mishap cost data (\$000) for natural phenomena to which improved weather radar may be a benefit

	Year					Mean
	76	77	78	79	80	
Hail	132	877	106	*	222	334
Hurricane/Typhoon	10053	140	8150	13464	21	6366
Lightning	9	198	52200	1818	83	10862
Rain	2	200	*	*	*	101
Sleet/Freezing Rain	25	*	*	*	*	25
Tornado	17	9	201	3751	140	824
Windstorm/High Winds	584	505	1213	686	2686	1135
Snow/Blizzard	308	23	380	9	*	180
Flood	*	*	211	6	83	100
Turbulence	*	*	19	0	*	10

(*) Data not available.

derived using the probabilities of detection, false alarm ratios, and critical success indicators obtained from JDOP test results, year 1).

	<u>Observed</u>			<u>Observed</u>	
	Y	N		Y	N
Y	500	1280	Y	1450	475
Forecast			Forecast		
N	200		N	75	
		Without Doppler			With Doppler

NEXRAD will reduce the number of false alarms (warnings when no severe weather occurs) by 805. As indicated in Case Study CS-14 of Appendix C, the cost of taking protective action is \$10,000 per warning. Total annual savings is \$8,050,000. Similarly NEXRAD will provide an improvement of forecast occurrence of severe thunderstorms by 950 forecasts. Since preventable damage is likely, from \$10,000 to \$1,000,000 per storm, we'll assume \$100,000 for an average; this totals \$95,000,000. So, NEXRAD will most likely reduce costs/losses by \$103 million per year at CONUS military units for severe thunderstorm warnings (Letter, HQ AWS, March 25, 1981, and Memo, April 15, 1981).

The value of NEXRAD for hurricane forecasting results from better prediction of the movement and intensity of the storms. As for

thunderstorms, NEXRAD will reduce the number of false alarm PWS. We estimate the 1.6 hurricanes per year that affect the southeastern United States will directly hit three major military installations. We assume they had time and took all the necessary precautions to minimize damage with or without NEXRAD. But NEXRAD would help the other 10 military installations that also took protective action but did not need to. As indicated in Case Studies CS-4 and CS-7 in Appendix C, each time protective action is taken, it costs the Government \$.5 million. Each year then, \$.5 million is saved by using NEXRAD to help issue better forecasts for hurricanes (Letter, HQ AWS, March 25, 1981).

General Cost Summaries

Table 31 is a general summary of the annual costs of hazardous weather in terms of lives lost, injuries, property loss, and other costs associated with weather disasters.

The figures in this report are based on a relatively short term search for available hazardous weather loss data. The bulk of the information was obtained from Federal sources. Additional information was obtained from insurance records, data from a wide variety of researchers, AMS publications, and personal contact with experts.

Thompson's estimate (1972) is based on a 3-year study under a research grant from NASA. The results are based on thousands of questionnaires that were sent to government, industry, commercial, and other organizations impacted by hazardous weather. They were asked to report on total hazardous weather losses experienced and to estimate what percentage of those losses might have been protected with a perfect forecast.

The 1973 Federal plan does not detail the basis for its \$15.0 billion estimate. Instead, it states that "using the statistics available, it appears that the 'order of magnitude' estimate of the total annual losses resulting from weather in the United States is about \$15 billion".

Table 31.--Annual average hazardous weather costs*

Hazard	Deaths	Injuries	Property Loss
Tornadoes	143	2,271	500 Million
Hurricanes	65	N/A	600 Million
Floods	200	N/A	1.0 Billion
Thunderstorms			
Lightning	200	245	100 Million
Hail	N/A	N/A	850 Million
Windstorms	100	N/A	500 Million
Severe Winter Storms	53	50	500 Million
Sub Total	761	2,566	4.050 Billion

Table 31.--Continued

Other Costs	
Red Cross Disaster Costs	25 Million
FEMA Disaster Costs	300 Million
Air Transportation Delays (Severe Weather)	160 Million
Construction/Manufacturing	1.500 Billion **
Communications/Energy	130 Million **
Other Transportation	96 Million **
Sub Total	2.221 Billion
Costs of Deaths and Injuries	
Deaths	630 Million
Injuries	310 Million
Sub Total	940 Million ***
Grand Total	\$7.201 Million

* Number of years varies depending on available statistics

** Based on Thompson's estimates

*** FAA calculations for deaths and injuries

In discussions with J.C. Thompson, he admits that various reviewers of his study have questioned the magnitude of his estimate. The interesting aspect of these criticisms is that they have been in both directions; some say the estimate is too high, while others say it is too low. Thompson's study was quite extensive and his estimates are based on a wealth of information gathered from a wide variety of weather users. Yet, in spite of the magnitude of his effort, Thompson recommended that some agency should sponsor a full scale study of the impacts of weather on man's activities, to include second order effects as well as the primary weather costs.

A general conclusion of this study is to reinforce Thompson's recommendation. The weakness of the data base concerning hazardous weather related costs is as evident now as it was when Thompson published his results in 1972. As was stated earlier, no Federal agency appears to have overall responsibility for maintaining records of losses associated with hazardous weather. Further, the second order costs of weather disasters, such as road repair, bridge rebuilding, railroad repairs, and a host of other costs related to weather disasters are not only not centrally maintained, they are generally not available at all or not available until some years after the weather-caused damage occurs. While, for example, Red Cross costs for disaster relief are generally available shortly after a disaster, FEMA costs may not be finalized for several years.

Thompson and the Federal Coordinator included approximately \$8 billion for agricultural losses--most of which are not included

here. When these agricultural losses are included, the cost estimate of this study closely approximates \$15.0 billion.

Insured losses are available, but through a wide variety of sources. Here also there appears to be no single source of information. The magnitude of uninsured losses is even less readily available. One analysis of severe storm damage in Iowa (Appendix C, CS-1) indicates uninsured losses equal to 50 percent of insured losses.

Another general conclusion of this survey is that the cost estimates in this study are conservative. Where Environment Data Information Service (EDIS) figures are used we have tended toward the lower side of the edis range of estimates. In addition, annual averages are based on edis estimates occasionally dating back 50 years.

Other estimates of hazardous weather losses support our contention that estimates of losses were often based on projections that were inaccurate or incomplete. The Wiggins report states that "Annual flood losses, for example, are "officially" estimated to be less than half of what most experts agree they really are".

Therefore, this estimate of hazardous weather costs was undertaken with some trepidation. These figures, to some extent, are approximations. Some double counting is possible but we have attempted to eliminate this source of error wherever possible.

Summary of Potential Benefits

Potential annual benefits estimated from the operational deployment of NEXRAD are between \$210 and 600 million. This estimate is based on a considerable reduction in the number of lives lost and injuries and in property loss estimated to result from operational deployment of a NEXRAD weather radar system.

The benefits result from the estimated performance improvement of Doppler and non-Doppler radars on each of nine hazardous weather phenomena. The performance improvement estimates are those of weather radar experts.

The breakout of these annual benefits is given in Table 32, Estimate of Annual Average Benefits, and are traceable as a percentage value of annual costs. See Table 31, Annual Average Hazardous Weather Costs.

Additional benefits not assessable in dollar values are realizable from NEXRAD deployment. Benefits to accrue in the fields of air pollution, nuclear plant safety, agriculture, and weather forecasting are not assessed. These additional benefits will add to the value of the NEXRAD system. To determine how much additional value will require further study and analysis.

Table 32.--Estimate of annual average benefits (\$ in millions)

Hazard	Prevented		Injuries	Value (\$)	Property and Other Losses Avoided	Total Value (\$)	Mean Value (\$)
	Deaths	Injuries					
Flash Flood	130 to 150*	M/T	1703 to 1817*	70.98 to 81.9	150 to 200	220.9 to 281.9	252.4
Tornadoes	107 to 114*	M/A	1703 to 1817*	58.4 to 62.4	25 to 50	(168.6 to 203.3)	186
Thunderstorms	16 to 20*	M/A	M/A	85.2 to 90.9	34.7	40.5 to 54.2	47.4
Hurricanes	M/T	M/A	M/A	5.8 to 19.5	53 to 60	61.6 to 78.5	66.3
Winds	M/T	M/T	M/T	8.7 to 10.9	2.5	2.5	2.5
Severe Winter Storms	M/T	M/T	M/T	--	19.0	19.0	19.0
Turbulence	M/A	M/A	M/A	--	M/T	--	--
Icing	M/A	M/A	M/A	--	M/A	--	--
Hail	M/A	M/A	M/A	--	M/T	--	--
Subtotal	253 to 284*	1703 to 1817*	For Lives and Injuries Property Losses Avoided	229 to 266	284 to 366.2	511.1 to 631.8	573.6
\$546,000/death						9229 to 266	
\$50,000/injury						276 to 366	
						\$505 to 632	

*Number of deaths/injuries prevented

M/A--Costs not available from data

M/T--Benefits not taken in dollar or percent in this study--See text for nature and estimate of value

In the next section, the analysis of the alternatives does not include dollar values for military benefits and for other benefits not taken in this chapter. Dollar values of benefits identified in Table 32 are used in the analysis.

ASSESSMENT OF ALTERNATIVES

Ground-based weather radar provides a unique capability to detect, locate, and track hazardous weather in the United States. There is no other adequate alternative system that is as cost-effective as weather radar in performing this function.

In this analysis, we have assumed a set of scenarios utilizing a total of 140 weather radars, in accordance with guidance from the NEXRAD JSPO. When a mixed system of Doppler and non-Doppler is assessed we have assumed 95 Doppler and 45 non-Doppler weather radars. The 95 Doppler radars are located in that section of the conterminous United States east of the Continental Divide where the frequency of hurricanes, tornadoes, and thunderstorms is highest. See Figure 27. The procedure for calculating the economic assessment of the proposed NEXRAD alternative configurations is outlined in Figure 28. In assessing radar performance, five types of weather radars configured in seven ways have had their performance assessed in detecting, locating, and measuring nine types of hazardous weather. Table 33 summarizes the relative performance of six scenarios in relation to each phenomenon with Scenario 7 serving as a baseline for comparison.

In estimating the dollar value of the potential benefits, the mean value of the range of benefits for each phenomenon indicated in Table 32 has been assigned to the performance of the weather radar (Type II) deployed in Scenario 2. Dollar values for the benefits associated with the other scenarios were computed as a function of the relative capability of the scenario. These data are summarized in Table 34.

To obtain an indication of the return on investment from deployment of each scenario, the total non-recurring cost of each scenario, as given in Table 4, together with a 5- to 6-year time frame for system acquisition is calculated using the dollar values of the benefits derived. See Table 34. These computations are summarized in Table 35 as the net present value after 25 years with discount rates of 10 percent. See Appendix F for details.

The analysis shows that the highest net present value is associated with the higher cost 5-beam Type I Doppler weather radars. Net present values associated with Scenarios 2 and 4 are quite close and reflect the increased performance capability associated with the Doppler radars utilizing more than a single antenna beam.

It is interesting to note that Scenario 4, mixed system with Type II Doppler radars and Type IV non-Doppler weather radars has a higher net present value than Scenario 3, which is made up of all Type III Doppler radars. This results from the fact that the mixed system scenarios are defined to locate the Doppler radars in those parts of the country where the Doppler capability makes an important



Figure 27.--Composite map of three hazardous weather phenomena with selected frequency/areas of occurrence.

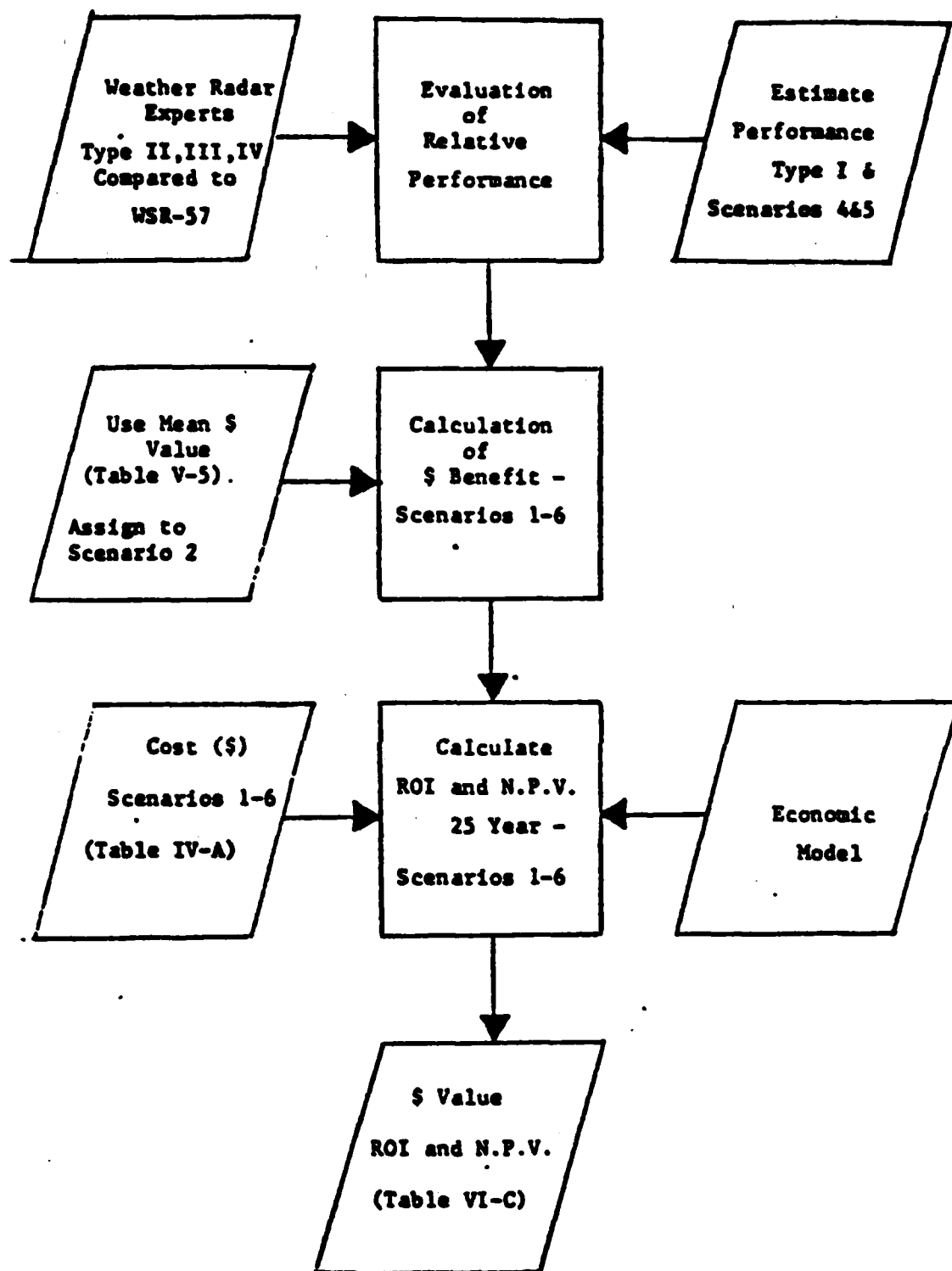


Figure 28.--Outline of procedure for economic assessment of alternatives

Table 33.--Relative performance of each scenario using Type V as equivalent to upgraded WSR-57 and weather radar experts estimate of performance improvements

Hazard	Radar Scenario						
	All 140 Type I	All 140 Type II	All 140 Type III	95-II and 45-IV	95-III and 45-IV	All 140 Type IV	All 140 Upgraded WSR-57
	(All Doppler)			(Mixed)		(Non-Doppler)	
Flash Floods	1.74	1.74	1.71	1.67	1.65	1.41	1.00
Tornadoes	2.40	2.34	1.95	2.25	1.85	1.20	1.00
Thunderstorm	1.80	1.75	1.53	1.65	1.43	1.25	1.00
Hurricane	1.75	1.71	1.60	1.71	1.60	1.22	1.00
Severe Winter Storm	1.60	1.56	1.41	1.56	1.41	1.19	1.00
Turbulence	2.30	2.23	1.97	1.95	1.75	1.20	1.00
Icing	1.18	1.18	1.16	1.17	1.15	1.09	1.00
Hail	1.70	1.66	1.44	1.60	1.38	1.24	1.00
Wind	2.10	2.08	2.00	1.95	1.94	1.08	1.00

Table 34.--Annual dollars potential benefits (\$ in millions)

Hazard	Radar Scenarios						Type V Upgraded WSR-57 All 140
	1	2	3	4	5	6	
	Type I All 140	Type II All 140	Type III All 140	95 of III 45 of IV	95 of III 45 of IV	Type IV All 140	
Flash Flood	\$252.4	\$252.4	\$242.2	\$228.5	\$ 221.7	\$ 139.8	\$ --
Tornado	194.3	186.0	131.9	173.5	118.0	27.8	--
Thunderstorm	50.6	47.4	33.5	41.1	27.2	15.8	--
Hurricane	70.0	66.3	56.0	66.3	56.0	20.5	--
Severe Winter Storms	20.4	19.0	13.9	19.0	13.9	6.4	--
Turbulence							--
Icing							--
Hail							--
Wind	2.5	2.5	2.3	2.2	2.2	0.2	--
Total	\$590.2	\$573.6*	\$479.8	\$530.6	\$439.0	\$210.5	--

*Mean Value of Table 29

difference. The non-Doppler radars are placed in regions where there is lower probability for the occurrence of tornadoes, hurricanes, and thunderstorms.

Table 35.--NEXRAD scenarios

Net Present Value, (25 Years) (dollars in millions)			
	Acquisition Cost	Recurring Cost	Net Present Value
Scenario 1	\$568	\$21	\$2206
Scenario 2	422	21	2142
Scenario 3	399	21	1841
Scenario 4	395	23	2013
Scenario 5	371	22	1740
Scenario 6	296	22	837
Scenario 7	--	--	--

Scenario 7 is the reference scenario

Scenario Configuration

Scenario 1	140 Type I Radars	5-Beam Doppler
Scenario 2	140 Type II Radars	2-Beam Doppler
Scenario 3	140 Type III Radars	1-Beam Doppler
Scenario 4	95 Type II, 45 Type IV Radars	Mixed, Doppler/ Non-Doppler
Scenario 5	95 Type III, 45 Type IV Radars	Mixed, Doppler/ Non-Doppler
Scenario 6	140 Type IV Radars	1-Beam non-Doppler
Scenario 7	140 Type V Radars	Sustained

Table 4 reflects the increased acquisition and operating costs associated with mixed systems and these costs were utilized in the net present value computations.

The largest percentage of total potential benefits result from savings anticipated from loss avoidance due to floods, tornadoes, thunderstorms, and hurricanes. In the case of floods, the difference in performance capability between Doppler and non-Doppler weather radars is small, so that non-Doppler radars that are located west of the thunderstorm and tornado belts could provide adequate coverage. This situation tends to reduce the difference in net present value of potential benefits between the all Doppler and the mixed systems.

Table 36 summarizes estimates of the total potential benefit of a NEXRAD System to the general civil sector, to civil aviation, and to the military. Most of the total potential benefits are seen to accrue to the civil sector. This is a reflection of the overall costs to the civil sector of floods, hurricanes, and tornadoes as compared with other hazardous weather phenomena and the fact that an improved weather radar network provides opportunities for significant costs avoidance.

Table 36.--Potential annual benefit to various sectors
(dollars in millions)

	All Sectors	General Public	Civil Aviation	Military
Flash Floods	\$252.4	\$252.4	N/T	N/T
Tornadoes	186.0	186.0	N/T	See ¹ Below
Thunderstorm	47.4	N/T	47.4	103.0 ¹
Hurricane	66.3	66.3	N/T	0.5 ¹
Severe Winter Storm	19.0	N/T	19.0	N/T
Wind	2.5	N/T	2.5	N/T
Turbulence*	N/T	N/T	N/T	N/T
Icing*	N/T	N/T	N/T	N/T
Hail*	N/T	N/T	N/T	See ¹ Below
Total	\$573.6	\$504.7	\$68.9	\$103.5 ¹
Grand Total	(\$677.1) ²			

¹ See Cost Benefits Related to Specific Users: Civil Aviation and Military for details

² Grand total including military benefits

N/T--Benefits not taken. Benefits for these phenomena have not been assessed in dollar values. We estimate significant benefits will result from NEXRAD use. Certain case studies in Appendix C suggest the nature of these benefits.

CONCLUSIONS

A preliminary assessment of the gains and benefits to be expected from improvements to the national system for detecting hazardous weather indicates that appreciable benefits will accrue from implementation of a new weather radar network by providing opportunity to prevent injury, loss of life, and damage to or loss of property, particularly those losses due primarily to flash flood, tornadoes, thunderstorms, and hurricanes. These benefits are conservatively estimated to be in the range of \$200 to 600 million annually, depending on the option chosen for implementation. Additional benefits are expected but not assessed quantitatively due to lack of sufficiently detailed information. These unquantified benefits also include those resulting from improved weather services dealing with non-hazardous weather phenomena.

The economic analysis of system alternatives shows that a full Doppler weather radar system will yield the highest benefits. The differences in net present value and benefit/cost ratios between the various Doppler configurations, including mixed systems of 95 Doppler and 45 non-Doppler, are relatively small. If different assumptions were to be made concerning the operational concept under which the various alternatives would be utilized, changes in the relative ranking of the alternatives could result.

System Configurations and Economic Indices

Scenario	Acquisition Cost	Net Present Value At 10% Discount	IRR (Percent)	Benefit/Cost Ratio
1	\$568 Million	\$2.206 Billion	40.9	11.94
2	422 Million	2.142 Billion	41.9	13.30
3	399 Million	1.841 Billion	40.9	11.71
4	395 Million	2.013 Billion	41.8	12.41
5	371 Million	1.740 Billion	42.1	10.82
6	294 Million	0.838 Billion	37.9	6.24

The table above, summarizing the economic indices for the scenarios, clearly shows that the value of implementing a NEXRAD System that includes Doppler weather radar is at least twice that for a system that does not include Doppler capability. Therefore, a primary conclusion that can be drawn from this analysis is that NEXRAD must pursue Doppler weather capability. Scenarios 4 and 5 are mixed configurations that include Doppler weather radars in regions of high probability of hazardous weather with non-Doppler weather radars in other areas. The fact that the Doppler weather radars are postulated for such regions results in the relatively high value of these mixed systems. The two-beam Doppler weather radar postulated for Scenario 2 results in the highest benefit/cost ratio, due primarily to the cost of the two-beam radar being significantly less than that for the five-beam system in Scenario 1.

The value of Scenario 4 is close to that of Scenario 2 because Scenario 4 would utilize the same two-beam Doppler weather radars in regions of high probability of hazardous weather.

Computations were made to test the sensitivity of the analysis to large changes in both the estimated annual benefit and overall cost of the radar systems. Annual benefits over the lifetime of the systems are so large that even if such benefits are assumed to be \$200 million less than estimated in this study, the net present value exceeds \$0.9 billion for all scenarios that include Doppler weather radars. A decrease in the estimated annual benefit could be caused by an increase in the annual operations and maintenance costs. Since such costs are estimated to be in the range of \$20 to 30 million, their doubling will have less impact than the assumed decrease in annual benefits described previously and net present values would remain above \$1 billion. Figure 29 is a plot of the net present value for each scenario that shows the sensitivity to variations in the estimated annual benefit.

Internal rate of return is the rate of discount that makes the present value of the benefits equal to the present value of the costs. As an investment criterion, the Internal Rate of Return (IRR) states that an investment should be made in a project that earns a rate of return (i.e., has an internal rate of return) equal to or in excess of the cost-of-capital rate. Assuming that the proper cost-of-capital rate is 10 percent, it can be seen that all of the scenarios meet this criterion. Figure 30 shows the bounds of the variation in the internal rate of return for the scenarios as the expected annual benefits changes. This figure also shows that the expected annual benefits can decrease by \$200 million before the internal rates of return for the scenarios reach 10 percent. On the other hand, if annual benefits are greater by only \$100 million, the internal rates of return increase rapidly beyond 100 percent.

The primary sensitivity of the analysis is in the performance and the operational capability that will be achieved by the operational NEXRAD network. Delay in system implementation will extend the time period of negative cash flow, delaying the time by which benefits can begin to accumulate. This provides one of the bases for the conclusion that operational techniques to fully exploit the Doppler capability should be pursued in parallel with the system development.

Table 36 shows that the greatest benefits will accrue to the general public with a lesser amount of benefit to civil aviation and the military. This conclusion is a strong function of the data base. As is true for many cost/benefit assessments, the data base for the determination of detailed hazardous weather costs is inadequate. Further assessment could demonstrate larger potential benefits both to civil aviation and to the military.

The primary focus of this study is hazardous weather detection and warning. The data base that is available is oriented toward the costs of catastrophic weather events. The value of Doppler weather radar information in improving overall forecast capability for more routine application has not been assessed. However, during the course of the study, clear evidence of the value of improved routine forecasts was seen. It is quite possible that the benefits that may result from improved routine forecasts may far outweigh the benefit that we have quantified during this assessment. Such evaluations, of course, are a part of the continuing assessment of "the value of weather" conducted by the National Weather Service.

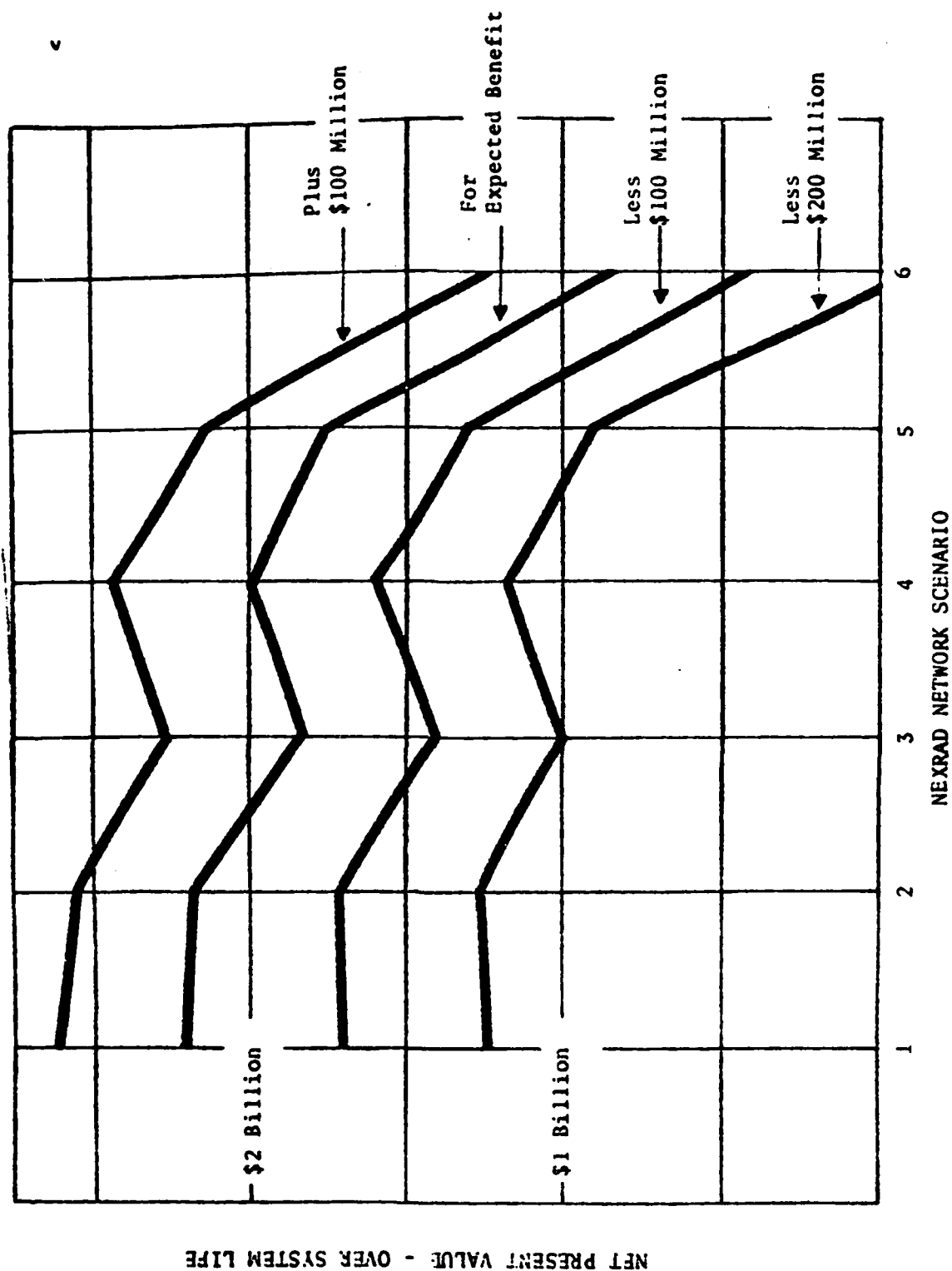


Figure 29.--Effect of benefit variation on value of NEXRAD over system life.

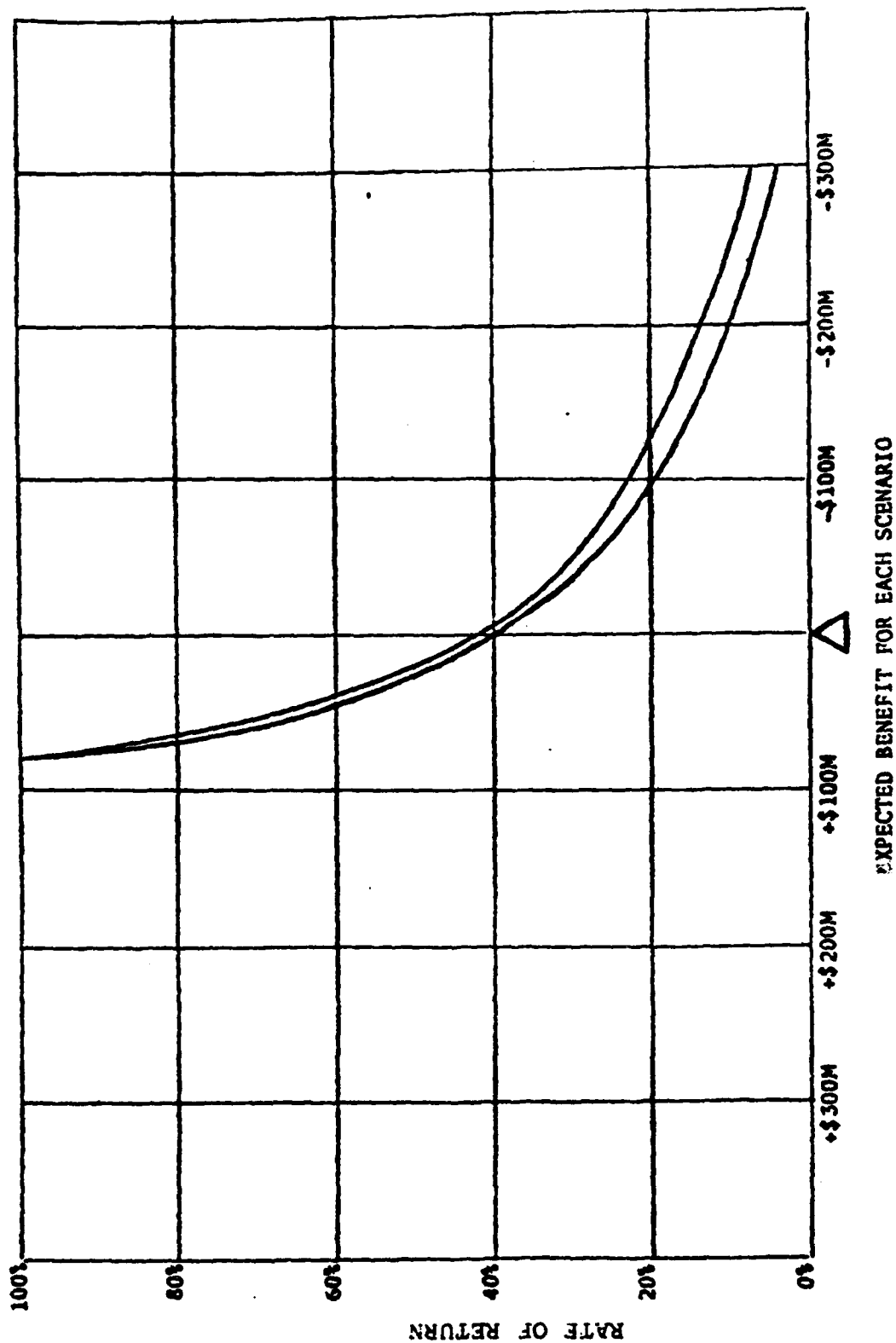


Figure 30.--Change in percentage rate of return versus benefit from expected value.

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